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A STUDY OF THREE PHASE AND SINGLE PHASE HIGH FREQUENCY DISTRIBUTION SYSTEMS

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The purpose of this research was to investigate the feasibility of multiphase high frequency power distribution systems driven by Schwarz converters. The two systems to be studied are a single phase parallel module cascaded Schwarz converter and a three phase cascaded Schwarz converter.

The single phase version consists of two power conditioning stages. The first stage contains a single Schwarz converter which operates in a variable frequency mode and acts as a regulated dc power supply. This mode of operation is used to maintain a regulated output voltage for the second stage of the system. The second stage consists of three Schwarz converters operated at a fixed switching frequency with the input and output of the converters connected in parallel. This arrangement produces an ac transmission system with a fixed frequency, regulated amplitude output voltage.

The three phase version also consists of two power conditioning stages. The first stage is exactly the same as the one for the single phase version. The second stage uses three-

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19. Abstract (Cont'd)

Schwarz converters operated a fixed switching frequency with a phase angle displacement of ∓120 degrees between adjacent phases. The converter inputs of second stage are connected in parallel and the outputs are connected in a three phase wye configuration. This arrangement produces a three phase ac transmission system with a fixed frequency, regulated voltage.

FOREWORD

This report presents the results of research performed under Subcontracts SCEEE-SRAP/87-4 and SCEEE-SRAP/88-4A which were performed by The University of Toledo for the U.S. Air Force Aero Propulsion Laboratory over the period March 1, 1987 to September 30, 1988. These subcontracts were administered by the Southeastern Center for Electrical Engineering Education, St. Cloud, Florida. The report is divided into two parts: Part I - A Comparison of Single vs. Three Phase High Frequency Distribution Systems, and Part II - Isolation of Faulted Modules in Series Resonant Converters. Part of the material for this report is also included in reference [18].

CONTENTS

PART I: A COMPARISON OF SINGLE VS. THREE PHASE HIGH FREQUENCY DISTRIBUTION SYSTEMS

Section I

INTRODUCTION FOR PART I

1.1 Background

The main purpose of this research is to investigate the feasibility of multiphase high frequency power distribution systems driven by Schwarz converters. The two systems to be studied are a single phase parallel module cascaded Schwarz converter and a three phase cascaded Schwarz converter. The general arrangements for the single phase and three phase versions are shown in Figure 1.1 and Figure 1.2 respectively.

The single phase version consists of two power conditioning stages. The first stage contains a single Schwarz converter which operates in a variable frequency mode and acts as a regulated dc power supply. This mode of operation is used to maintain a regulated output voltage, V_{O2}, for the second stage of the system. The second stage consists of three Schwarz converters operated at a fixed switching frequency with the input and output of the converters connected in parallel. This arrangement produces an ac transmission system with a fixed frequency, regulated amplitude output voltage.

The three phase version also consists of two power conditioning stages. The first stage is exactly the same as the one described for the single phase version. The second stage uses three Schwarz converters operated at a fixed switching frequency with a phase angle displacement of ±120 degrees between adjacent phases. The converter inputs of the second stage are connected in parallel and the outputs are connected in a three phase wye configuration. This arrangement produces a three phase ac transmission system with a fixed frequency, regulated voltage.

The use of the three Schwarz converters in the second stage of the single phase version was used to provide a system that produced almost the same maximum output power as the three phase system. Also, as the amount of power to be processed increases, modularizing the stages becomes an important alternative to a single stage. Therefore, the operating characteristics of a modularized system in a parallel single phase or a three phase connection can be readily investigated.

Schematic diagrams and a parts list of the circuits used for the single phase parallel module cascaded Schwarz converter can be found in Appendix A. Appendix B contains the same information for the three phase cascaded Schwarz converter.

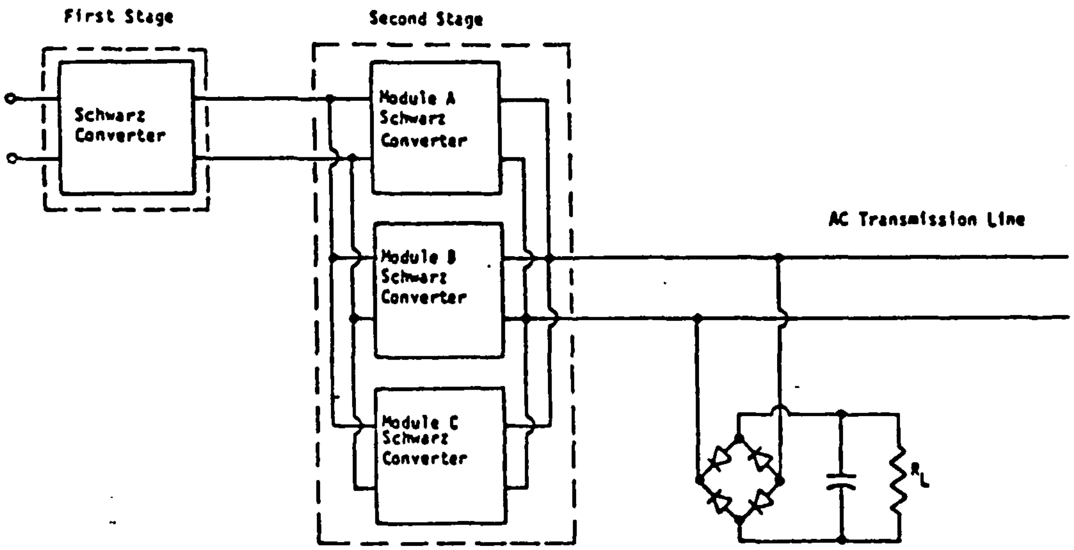


Figure 1.1: Single Phase Cascaded Schwarz Converter General Arrangement

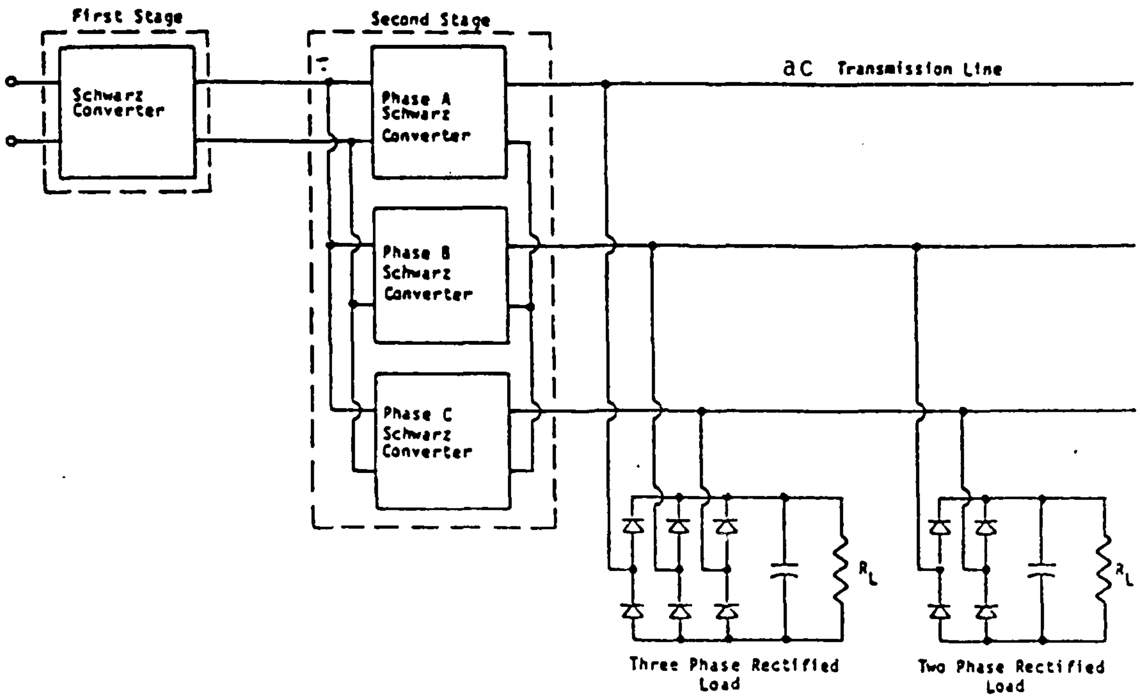


Figure 1.2: Three Phase Cascaded Schwarz Converter General Arrangement

1.2 Previous Research

Several articles have been presented on the subject of series resonant converters (e.g. Schwarz converters). References [1-7] provide a sample of the technical literature available on these circuits. In reference [1], Schwarz presents a closed form solution for the steady-state operating point of the half bridge series resonant converter without antiparallel diodes. By excluding the antiparallel diodes, this circuit is constrained to a discontinuous current mode of operation. In reference [2], Schwarz derives a closed form solution for the steady-state operating point of the half bridge series resonant converter including the antiparallel diodes. A normalized closed form solution for the steady-state operating point of the half bridge series resonant converter is derived in reference [3] by King and Stuart. This normalized solution addresses both the continuous and discontinuous current modes of operation.

The above mentioned references provide the basis for the derivation of the equations describing the full bridge series resonant converter. In references [4-5] Schwarz formulates the equation describing the full bridge series resonant converter. In reference [6], Vorperian and Cuk present a complete dc analysis of the full bridge series resonant converter. In reference [7], King and Stuart present a normalized closed form solution for the steady-state operating point of the full bridge series resonant converter.

In references [8] and [9], King and Stuart discuss the parallel operation of Schwarz converters. A normalized set of simultaneous nonlinear equations for the steady-state operating point is found for a general system of N parallel converters. These equations can be solved using an iterative technique. Also, a set of normalized network equations is given describing the operation of this circuit at the steady-state operating point. Theoretical and experimental results are presented for a system of two Schwarz converters operated in parallel. In references [8] and [10], Ray and Stuart discuss the operation of a single phase cascaded Schwarz converter. For the circuit of references [8] and [10], the second stage consisted of a single Schwarz converter as opposed to the three parallel converters used in this present research. A normalized set of simultaneous nonlinear equations for the steady-state operating point is in these references. These equations can be solved using an iterative technique. Also, normalized equations are given for several steady-state variables of interest.

Recently there have been a few articles which discuss multiphase high frequency distribution systems. References [11' and [12] introduce a system, shown in Figure 1.3, of N parallel connected Schwarz converters. Each phase of this system operates at the same switching frequency but with a phase angle displacement of $2\pi/N$ radians between adjacent phases. This system is similar to the arrangement used for the second stage of the three phase Schwarz converter used in this present research. The difference between the circuit of references [11] and [12] and the proposed three phase system lies in the load connection. The multiphase system of references [11] and [12] supplies a common dc output, while the proposed three phase system supplies a common multiphase ac bus that may have any number of loads transformed to different voltages.

1.3 Objective

As mentioned previously, two high frequency power distribution systems will be studied. The first system is a single phase version of the cascaded Schwarz converter with the second stage consisting of three parallel converter modules operated at a fixed switching frequency. The second system will be a three phase version of the cascaded Schwarz converter where the three converters of the second stage are operated at a fixed switching frequency but with a ±120 degree phase shift between adjacent phases.

These systems will be studied to determine their operating characteristics, filter requirements, fault tolerance and operation with rectified loads. In addition, a design procedure will be developed for the two systems to aid in the selection of the major components used in these converters.

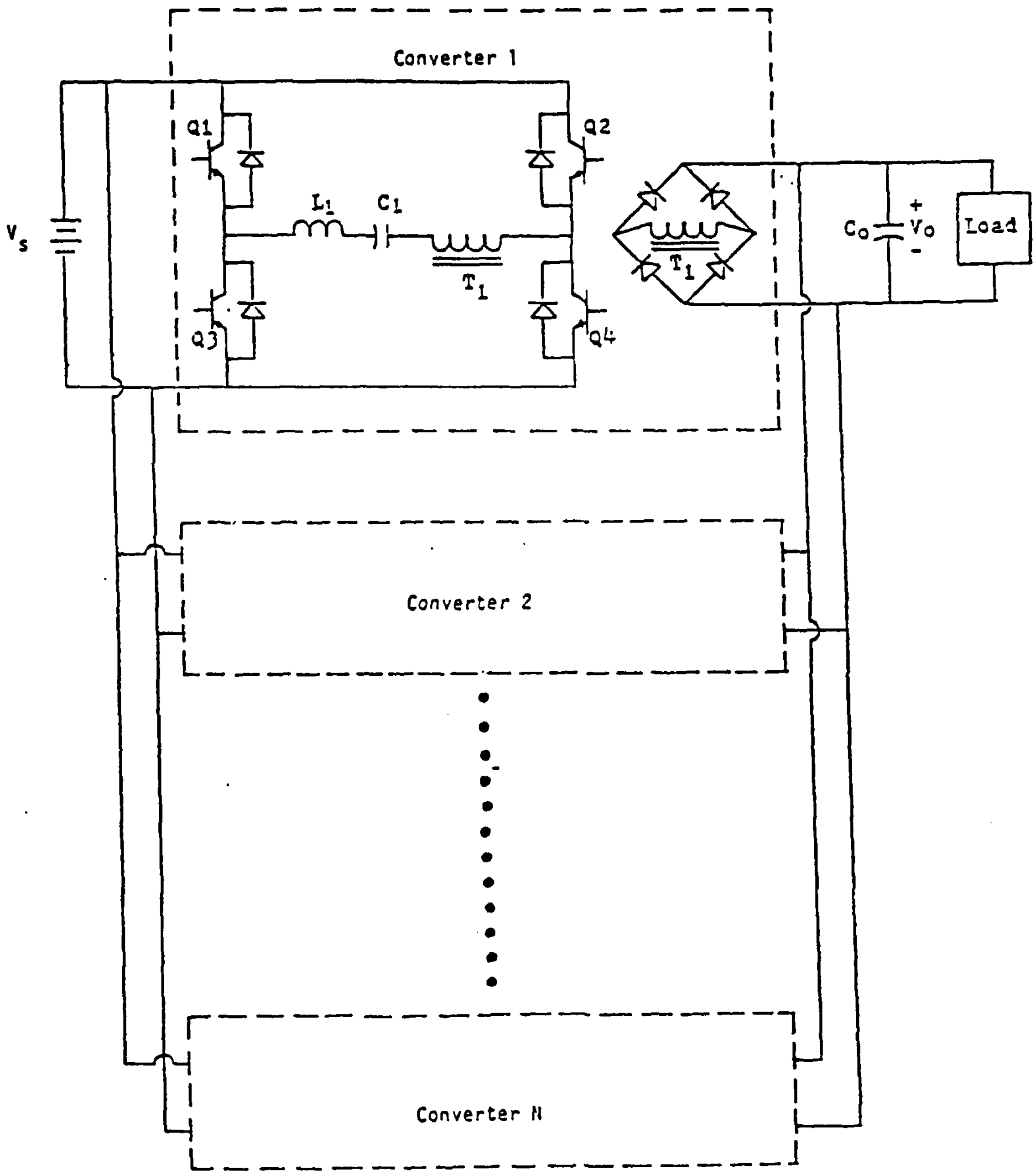


Figure 1.3: Multiphase Schwarz Converter with Single dc Output

Section II

DESIGN OF THE SINGLE PHASE AND THREE PHASE CASCADED SCHWARZ CONVERTER

2.1 *Steady-State Analysis of the Single Phase Cascaded Schwarz Converter.*

The basic block diagram of the cascaded Schwarz converter is shown below in Figure 2.1. Typical inverter output voltage and current waveforms for the first and second stages are shown in Figure 2.2. Assuming that the isolation transformers TR1 and TR2 of Figure 2.1 have a one-to-one turns ratio, Figure 2.1 can be modified and represented by the block diagram of Figure 2.3. By including the rectifier bridges RB1 and RB2 into the stage 1 and 2 blocks, respectively and by including the appropriate control variables, the final block diagram for the cascaded Schwarz converter used in the steady-state analysis is presented in Figure 2.4.

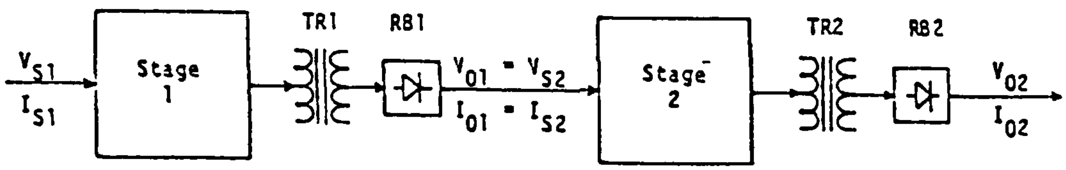


Figure 2.1: Basic Block Diagram of the Cascaded Schwarz Converter

The Schwarz converter in the first state of this system is driven by a variable frequency oscillator. This control scheme, which is described in reference [12], is referred to as a γ controller since the explicit control variable is the angle γ_1 (see Figure 2.2). The Schwarz converter of the second stage is also controlled by a γ controller. However, in this case $\gamma 2$ is kept constant by maintaining a constant drive frequency. Since γ_2 is constant, the explicit control variable for the second stage of the cascaded Schwarz converter is V_{S2}. V_{S2} is used to regulate the output voltage, V_{02}, of the second state.

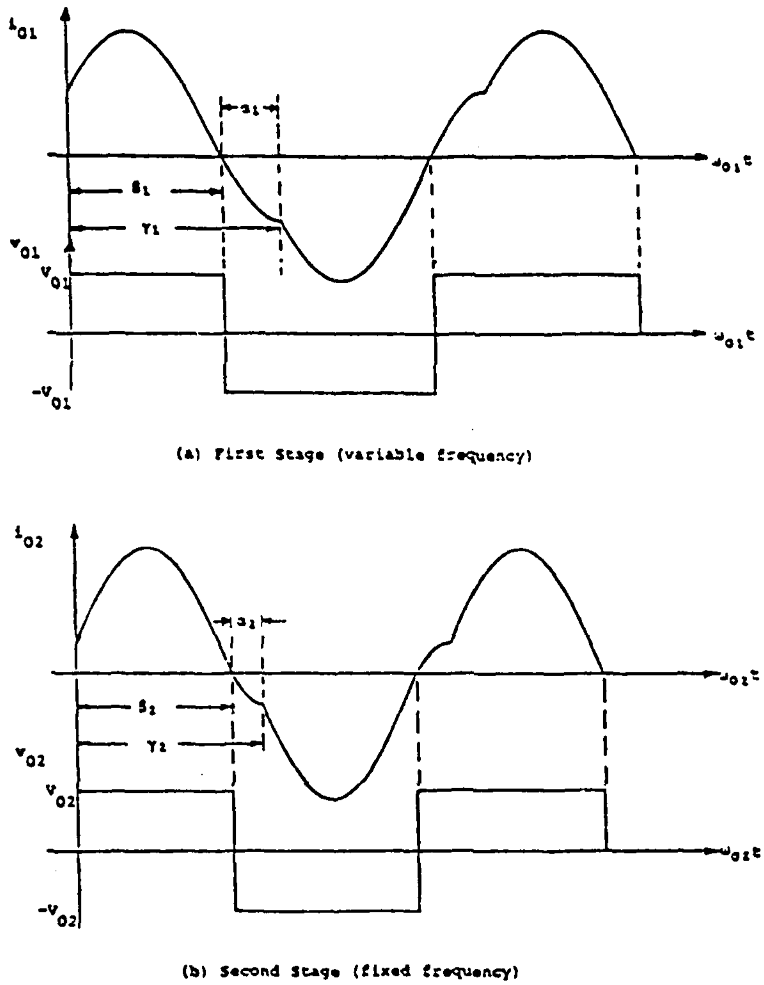


Figure 2.2: Typical Inverter Output Voltage and Current Waveforms

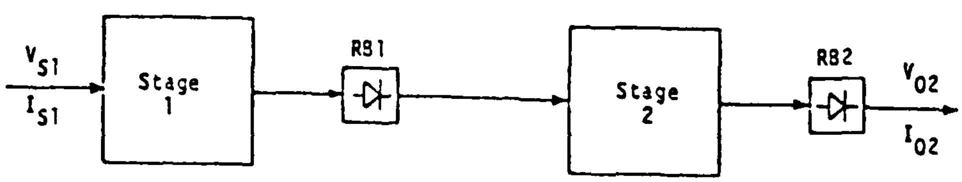


Figure 2.3: Modified Block Diagram of the Cascaded Schwarz Converter.

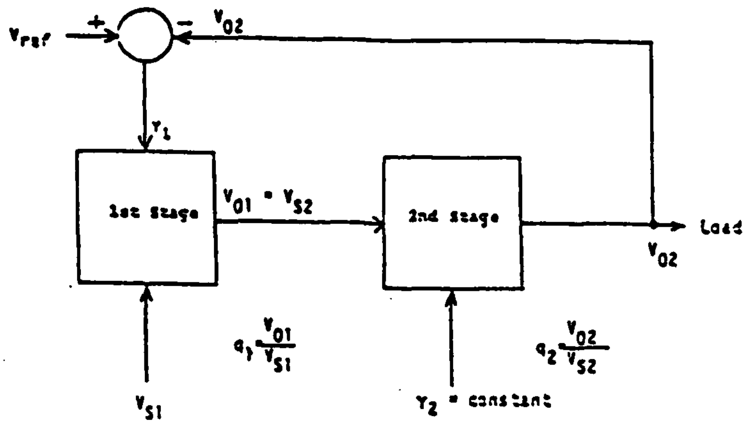


Figure 2.4: **Block Diagram of the Cascaded Schwarz Converter Used for the Steady-State Analysis**

The steady-state analysis of the cascaded Schwarz converter is given in references [8] and [10] and repeated here for convenience. The following quantities are defined in references [1-3], where the subscripts 1 and 2 refer to stages 1 and 2 respectively.

$$q_1 = \frac{V_{O1}}{V_{S1}}, \quad q_2 = \frac{V_{O2}}{V_{S2}}, \quad q_{12} = \frac{V_{O2}}{V_{S1}} = q_1\, q_2 \tag{2.1}$$

$$Z_{01} = \sqrt{\frac{L_1}{C_1}}, \quad Z_{02} = \sqrt{\frac{L_2}{C_2}}, \quad k_{12} = \frac{Z_{01}}{Z_{02}}, \tag{2.2}$$

$$f_{01} = \frac{1}{2\pi\sqrt{L_1C_1}}, \quad f_{02} = \frac{1}{2\pi\sqrt{L_2C_2}}, \quad \gamma_1 = \pi\frac{f_{01}}{f_{S1}}, \quad \gamma_2 = \pi\frac{f_{02}}{f_{S2}}, \tag{2.3}$$

where $f_{01} > f_{S1}$ and $f_{02} > f_{S2}$. Note f_{01} and f_{01} are the resonant frequencies of stage one and two respectively, f_{S1} is the actual operating frequency of stage one and f_{S2} is the fixed operating frequency of stage two. Figures A.2 and A.9 of Appendix A show the location of the resonant components L_1, C_1, and L_2, C_2 respectively. Also, the control variable for the second stage will be defined as q_2 which is more convenient to use than V_{S2}.

From reference [7], the average output current of a Schwarz converter is,

$$I_A = \frac{V_S}{Z_0}\,\frac{2(1+q)(1-\cos(\alpha))}{\gamma(q-\cos(\alpha))}. \tag{2.4}$$

Referring to Figure 2.4 and ignoring the system losses, we have the following equation,

$$V_{S2}I_{S2} = V_{02}I_{A2} \tag{2.5}$$

or

$$I_{S2} = q_2 I_{A2} \tag{2.6}$$

where all the above quantities are average values. Also from Figure 2.4, the average output current, I_{A1}, of stage 1 equals the average input current, I_{S2}, to stage 2. Therefore equation (2.6) becomes,

$$I_{A1} = q_2 I_{A2} \tag{2.7}$$

By substituting equation (2.4) into equation (2.7) with the appropriate subscripts included, we have

$$\frac{V_{S1}}{Z_{01}}\,\frac{2(1+q_1)(1-\cos(\alpha_1))}{\gamma_1(q_1-\cos(\alpha_1))} = q_2\frac{V_{S2}}{Z_{02}}\,\frac{2(1+q_2)(1-\cos(\alpha_2))}{\gamma_2(q_2-\cos(\alpha_2))} \tag{2.8}$$

or after simplification and noting the definitions of equation (2.1), equation (2.8) becomes

$$\frac{(1+q_1)(1-\cos(\alpha_1))}{(q_1+q_{12})(1-\cos(\alpha_2))} = \frac{q_{12}k_{12}\gamma_1(q_1-\cos(\alpha_1))}{\gamma_2(q_{12}-q_1\cos(\alpha_2))}. \tag{2.9}$$

Also from reference [7] and substituting in the appropriate subscripts, we have

$$\tan(\gamma_1-\alpha_1-\pi) = \frac{(q_1^2-1)\sin(\alpha_1)}{2q_1-(1+q_1^2)\cos(\alpha_1)} \tag{2.10}$$

and

$$\tan(\gamma_2-\alpha_2-\pi) = \frac{(q_2^2-1)\sin(\alpha_2)}{2q_2-(1+q_2^2)\cos(\alpha_2)}. \tag{2.11}$$

Substituting $q_2 = q_{12}/q_1$, equation (2.11) becomes,

$$\tan(\gamma_2-\alpha_2-\pi) = \frac{(q_{12}^2-q_1^2)\sin(\alpha 2)}{2q_1q_{12}-(q_1^2+q_{12}^2)\cos(\alpha_2)}. \tag{2.12}$$

Equations (2.9), (2.10) and (2.12) form a set of three simultaneous nonlinear equations that can be solved numerically for q_1, α_1 and α_2 with γ_1 as the input variable. This also determines q_2 since $q_2 = q_{12}/q_1$. The quantities k_{12}, q_{12} and γ_2 are considered to be known parameters. This procedure is summarized in Table 1.

In this present analysis, γ_1, is used as the first stage control variable. This differs from references [8] and [10] which use α_1. Note that γ_1 is an explicit control variable since frequency control is used and $\alpha 1$ is only an implicit control variable. This change has no effect on the equations, but it does change the variables which are considered known and unknown. Using γ_1 as the control variable was considered to be more appropriate since it is inversely proportional to the operating frequency.

Once a solution for the unknown variables is determined, several variables which describe the operation of the cascaded Schwarz converter can be calculated in a normalized form. These equations are given in reference [7] and repeated here for convenience. Note, the subscript N indicates the normalized value of the variable (i.e. the normalized average output current of stage 1 = I_{A1N}). To find the actual value each normalized quantity is multiplied by its appropriate base quantity.

Table 1: Summary of Equations to Find the Steady-State Operating Point.

Known Variables: $k_{12}, q_{12}, \gamma_1, \gamma_2$

Unknown Variables: $q_1, q_2, \alpha_1, \alpha_2$

Equations:

$$\frac{(1+q_1)(1-\cos(\alpha_1))}{(q_1+q_{12})(1-\cos(\alpha_2))} - \frac{q_{12}k_{12}\gamma_1(q_1-\cos(\alpha_1))}{\gamma_2(q_{12}-q_1\cos(\alpha_2))} = 0 \tag{2.13}$$

$$\tan(\gamma_1-\alpha_1-\pi) - \frac{(q_1^2-1)\sin(\alpha_1)}{2q_1-(1+q_1^2)\cos(\alpha_1)} = 0 \tag{2.14}$$

$$\tan(\gamma_2-\alpha_2-\pi) - \frac{(q_{12}^2-q_1^2)\sin(\alpha_2))}{2q_1q_{12}-(q_1^2+q_{12}^2)\cos(\alpha_2))} = 0 \tag{2.15}$$

$$q_2 = \frac{q_{12}}{q_1} \tag{2.16}$$

Equations (2.13), (2.14) and (2.15) are used to find a numerical solution for the unknown variables $q1$, $\alpha1$ and $\alpha2$. The value of $q2$ is found from equation (2.16).

Stage 1:

Base Voltage = V_{S1}

Base Impedance = $Z_{01} = \sqrt{\dfrac{L_{01}}{C_{01}}}$

Base Current = $\dfrac{V_{S1}}{Z_{01}}$

The normalized average output current is

$$I_{A1N} = \frac{2(1+q_1)(1-\cos(\alpha_1))}{\gamma_1(q_1-\cos(\alpha_1))}. \tag{2.17}$$

The normalized peak current is

$$I_{PK1N} = \frac{(1+q_1^2-2q_1\cos(\alpha_1))}{(q_1-\cos(\alpha_1))}. \tag{2.18}$$

The normalized average transistor current is

$$I_{QA1N} = \frac{(1 + q_1)\, I_{A1N}}{4}. \tag{2.19}$$

The normalized average diode current is

$$I_{DA1N} = \frac{(1 - q_1)\, I_{A1N}}{4}. \tag{2.20}$$

The normalized RMS current is

$$I_{R1N} = [\frac{1}{\gamma_1} [I_{01N}^2\left(\frac{\beta_1}{2} + \frac{\sin(2\beta_1)}{4}\right) + (V_{C01N} + 1 - q_1)^2\left(\frac{\beta_1}{2} - \frac{\sin(2\beta_1)}{4}\right) \tag{2.21}$$

$$+ I_{01N}(V_{C01N} + 1 - q_1)\sin^2(\beta_1) + (V_{C11N} + 1 - Q_1)^2\left(\frac{\alpha_1}{2} - \frac{\sin(2\alpha_1)}{4}\right)]]^{\frac{1}{2}}$$

where

$$I_{01N} = \frac{(1 - q_1^2)\sin(\alpha_1)}{(q_1 - \cos(\alpha_1))}, \tag{2.22}$$

$$V_{C01N} = \frac{q_1(1 + q_1)(1 - \cos(\alpha_1)}{(q_1 - \cos(\alpha_1))}, \tag{2.23}$$

$$V_{C11N} = -\frac{V_{C01n}}{q_1} \tag{2.24}$$

and

$$\beta_1 = \pi + \tan^{-1}\left[\frac{(q_1^2 - 1)\sin(\alpha_1)}{2q_1 - (1 + q_1^2)\cos(\alpha_1)}\right]. \tag{2.25}$$

The normalized peak capacitor voltage is

$$V_{CPK1N} = -\ V_{C11N}. \tag{2.26}$$

The equations for the second stage are similar to equations (2.17) through (2.26) except that V_{02} is chosen to be the base voltage instead of V_{S2} since V_{S2} varies as γ_1 varies. By using V_{02} as the base voltage, the equations describing the operation of the second stage are as follows:

Stage 2:

Base Voltage = V_{02}

Base Impedance = $Z_{02} = \sqrt{\frac{L_{02}}{C_{02}}}$

Base current = $\frac{V_{02}}{Z_{02}}$

The normalized average output current is

$$I_{A2N} = \frac{2(1 + q_2)(1 - \cos(\alpha_2))}{\gamma_2 q_2 (q_1 - \cos(\alpha_1))}. \tag{2.27}$$

The normalized peak current is

$$I_{PK2N} = \frac{(1 + q_2^2 - 2q_2 \cos(\alpha_2))}{q_2 (q_2 - \cos(\alpha_2))}. \tag{2.28}$$

The normalized average transistor current is

$$I_{QA2N} = \frac{(1 + q_2)\, I_{A2N}}{4}. \tag{2.29}$$

The normalized average diode current is

$$I_{DA2N} = \frac{(1 - q_2)\, I_{A2N}}{4}. \tag{2.30}$$

The normalized RMS current is

$$I_{R2N} = [\frac{1}{\gamma_2} [I_{02N}^2 \left(\frac{\beta_2}{2} + \frac{\sin(2\beta_2)}{4}\right) + (V_{C02N} + \frac{1}{q_2} - 1)^2 \left(\frac{\beta_2}{2} - \frac{\sin(2\beta_2)}{4}\right) \tag{2.31}$$

$$+ I_{02N} (V_{C02N} + \frac{1}{q_2} - 1) \sin^2(\beta_2) + (V_{C12N} + \frac{1}{q_2} - 1)^2 \left(\frac{\alpha_1}{2} - \frac{\sin(2\alpha_1)}{4}\right)]]^{\frac{1}{2}}$$

where,

$$I_{02N} = \frac{(1 - q_2^2)\sin(\alpha_2)}{q_2(q_2 - \cos(\alpha_2))}, \tag{2.32}$$

$$V_{C02N} = \frac{(1 + q_2)(1 - \cos(\alpha_2))}{(q_2 - \cos(\alpha_2))}, \tag{2.33}$$

$$V_{C12N} = -\frac{V_{C02n}}{q_2} \tag{2.34}$$

and

$$\beta_2 = \pi + \tan^{-1}\left[\frac{(q_2^2 - 1)\sin(\alpha_2)}{2q_2 - (1 + q_2^2)\cos(\alpha_2)}\right]. \tag{2.35}$$

The normalized peak capacitor voltage is

$$V_{CPK2N} = V_{C12N}. \tag{2.36}$$

In reference [7] normalized parametric curves are plotted for the equations describing the operation of a single stage Schwarz converter. Normaized parametric curves for equations (2.17) through (2.36) cannot be plotted for fixed values of q_1 and q_2 as in reference [7] because q_1 and q_2 now vary with γ_1. Therefore, normalized parametric curves for equations (2.17) through (2.36) are plotted versus γ_1 for fixed values of q_{12}, which do not vary with γ_1. These plots are presented in Figure 2.5 through Figure 2.16.

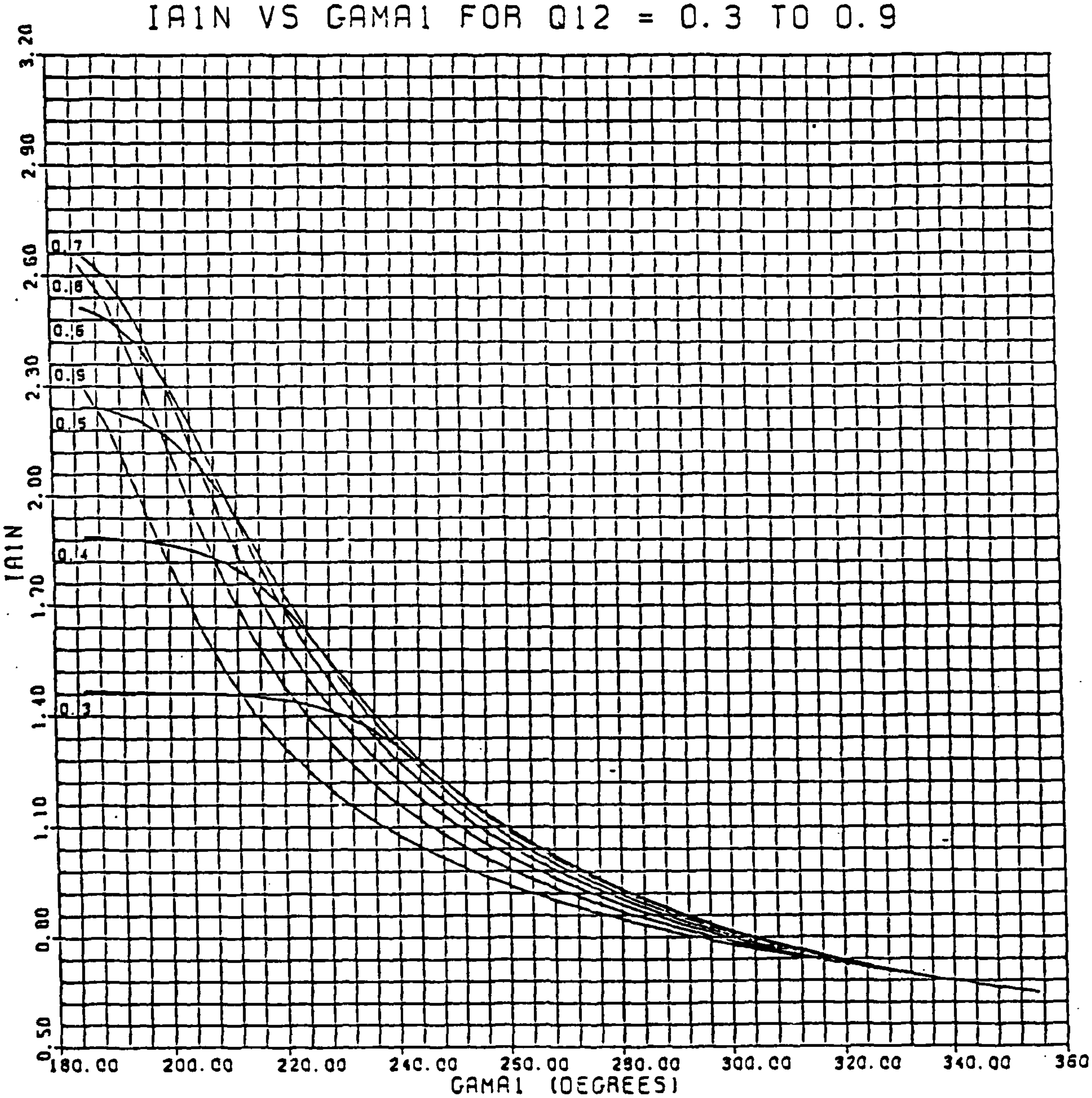


Figure 2.5: Single Phase Cascaded Schwarz Converter, IA1N vs. GAMMA1. Curves are parametric for Q12 = 0.3 to 0.9.

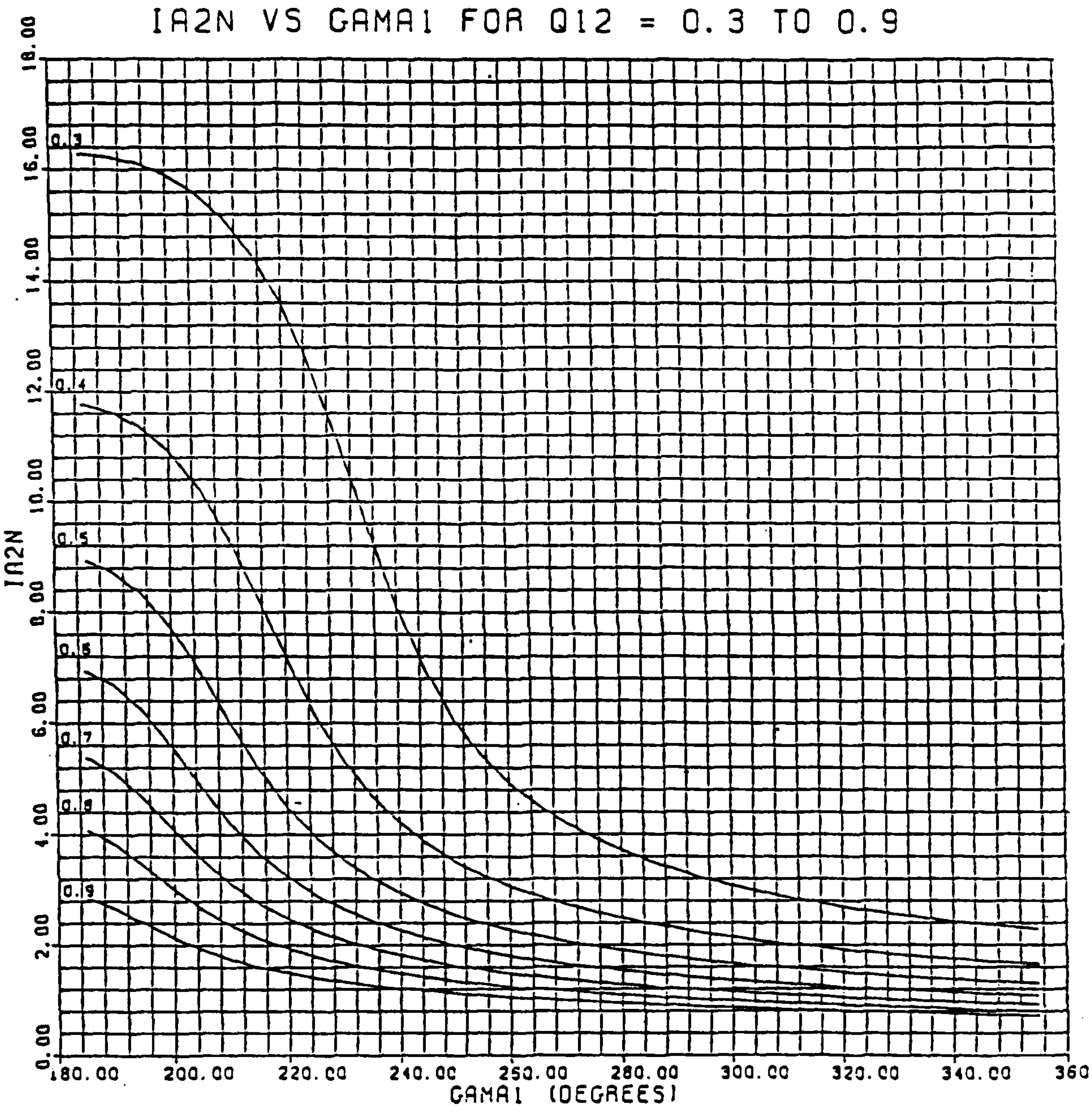


Figure 2.6: Single Phase Cascaded Schwarz Converter, IA2N vs. GAMMA1. Curves are parametric for Q12 = 0.3 to 0.9.

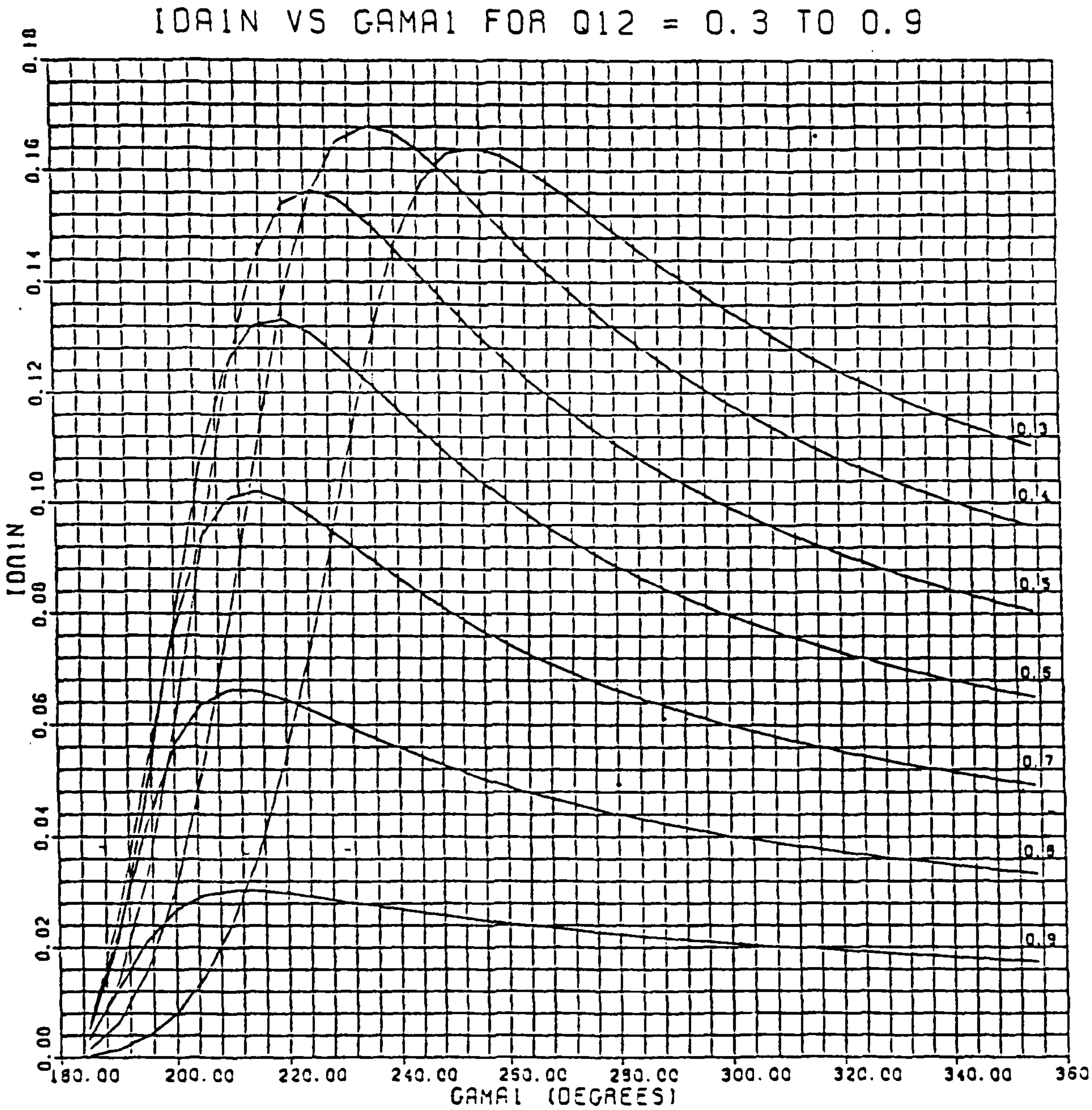


Figure 2.7: Single Phase Cascaded Schwarz Converter, IDA1N vs. GAMMA1. Curves are parametric for Q12 = 0.3 to 0.9.

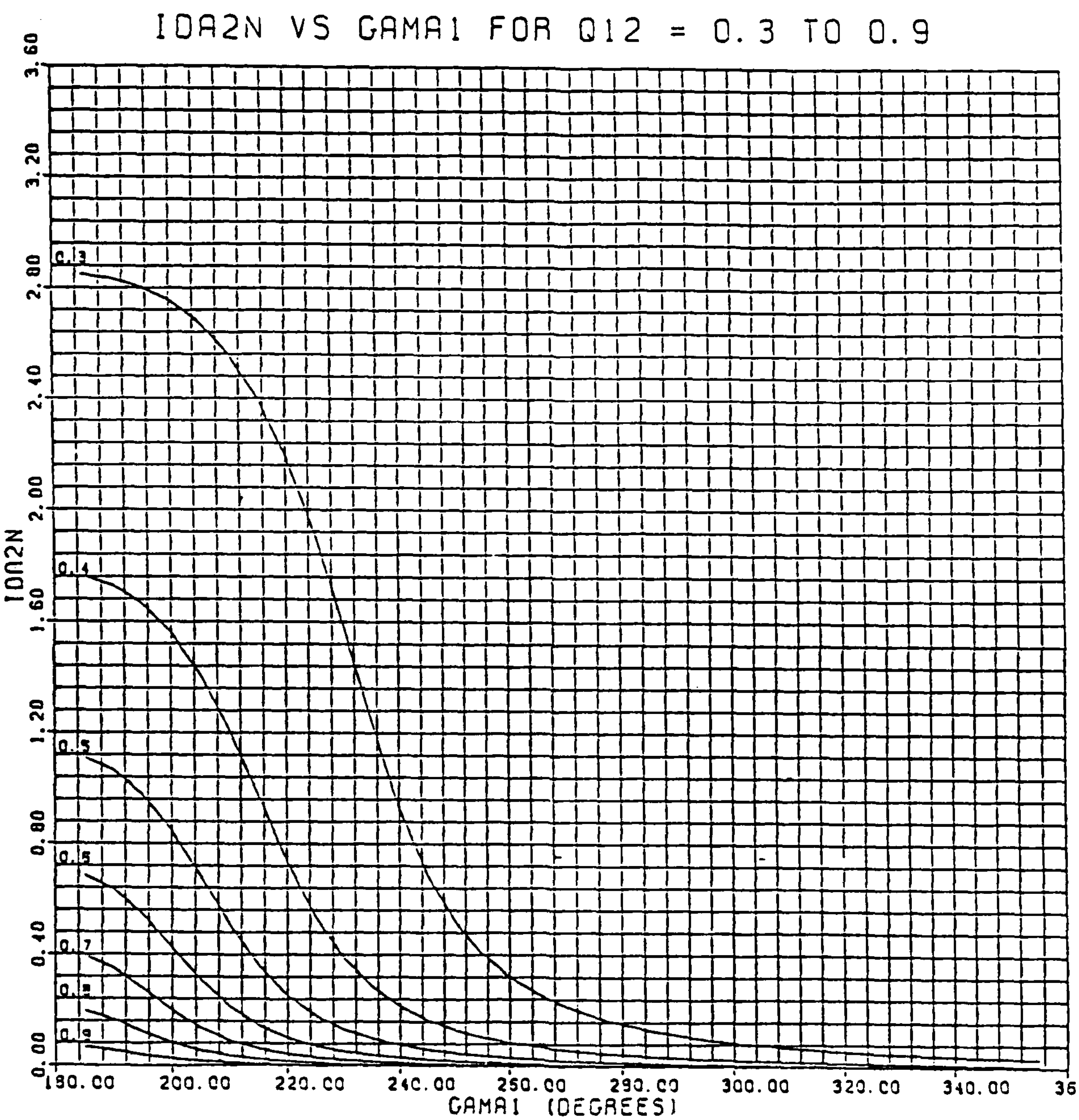


Figure 2.8: Single Phase Cascaded Schwarz Converter, IDA2N vs. GAMMA1. Curves are parametric for Q12 = 0.3 to 0.9.

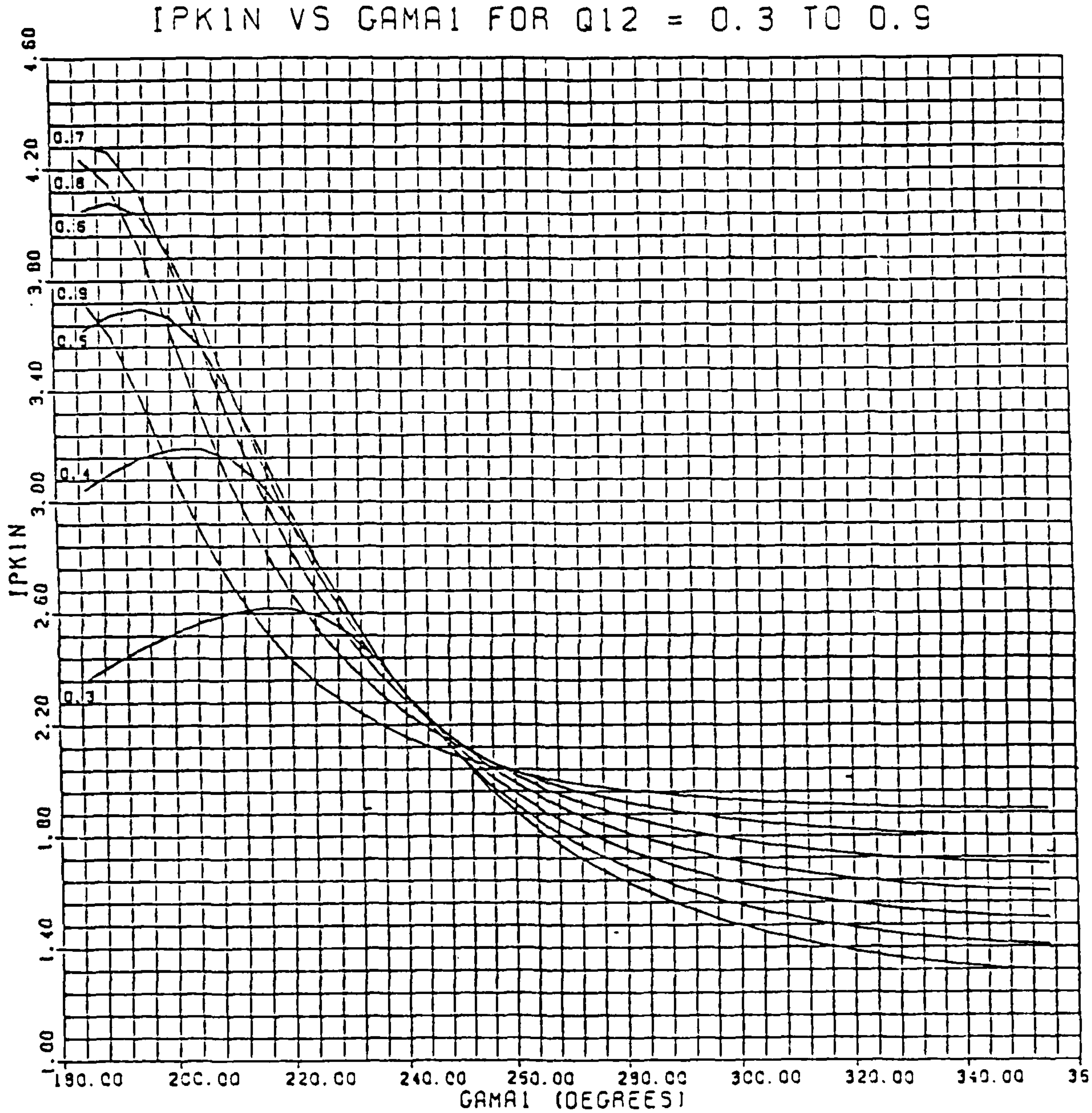


Figure 2.9: Single Phase Cascade Schwarz Converter, IPK1N vs. GAMMA1. Curves are parametric for Q12 = 0.3 to 0.9.

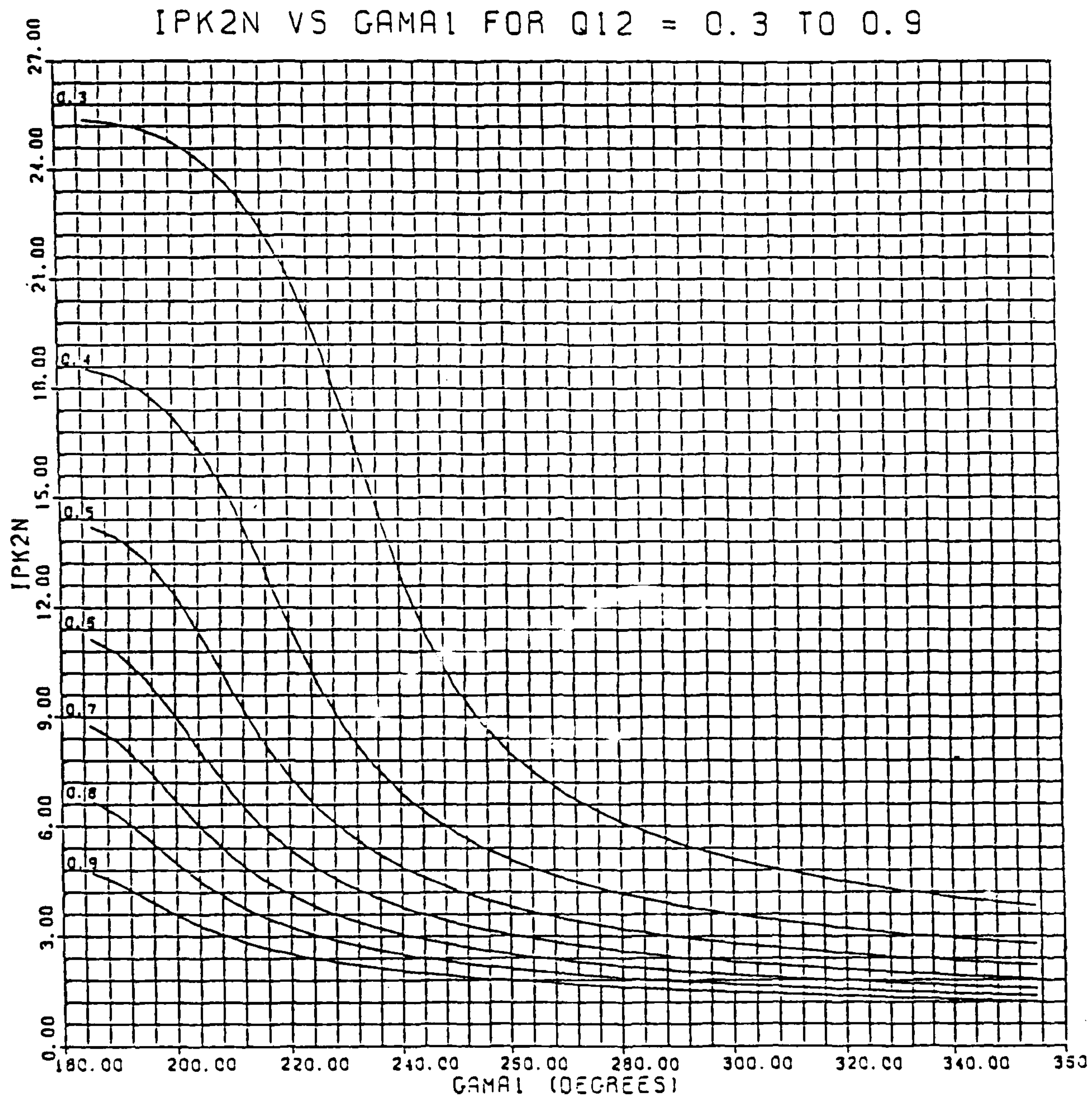


Figure 2.10: Single Phase Cascaded Schwarz Converter, IPK2N vs. GAMMA1. Curves are parametric for Q12 = 0.3 to 0.9.

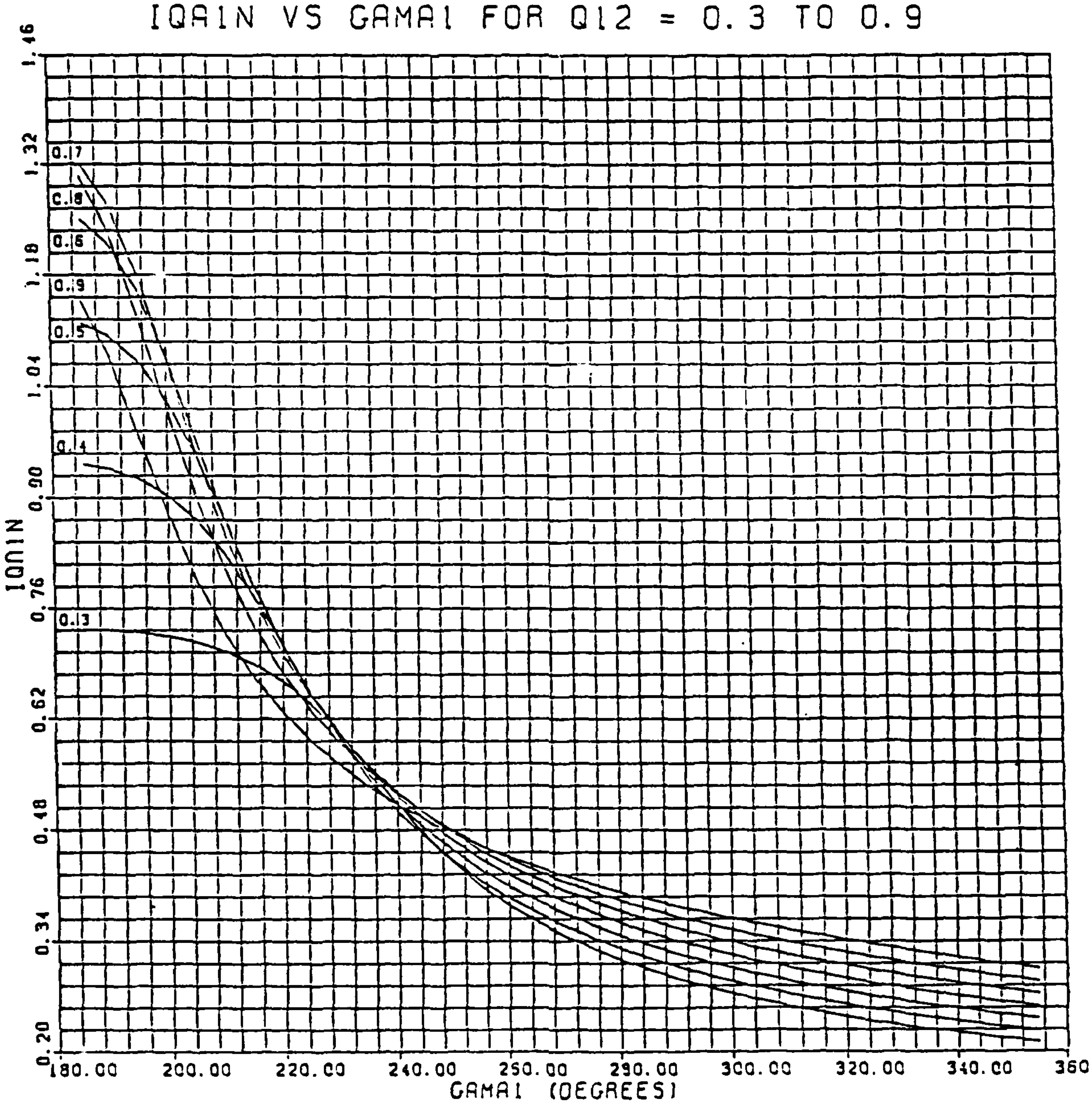


Figure 2.11: Single Phase Cascaded Schwarz Converter, IQA1N vs. GAMMA1. Curves are parametric for Q12 = 0.3 to 0.9.

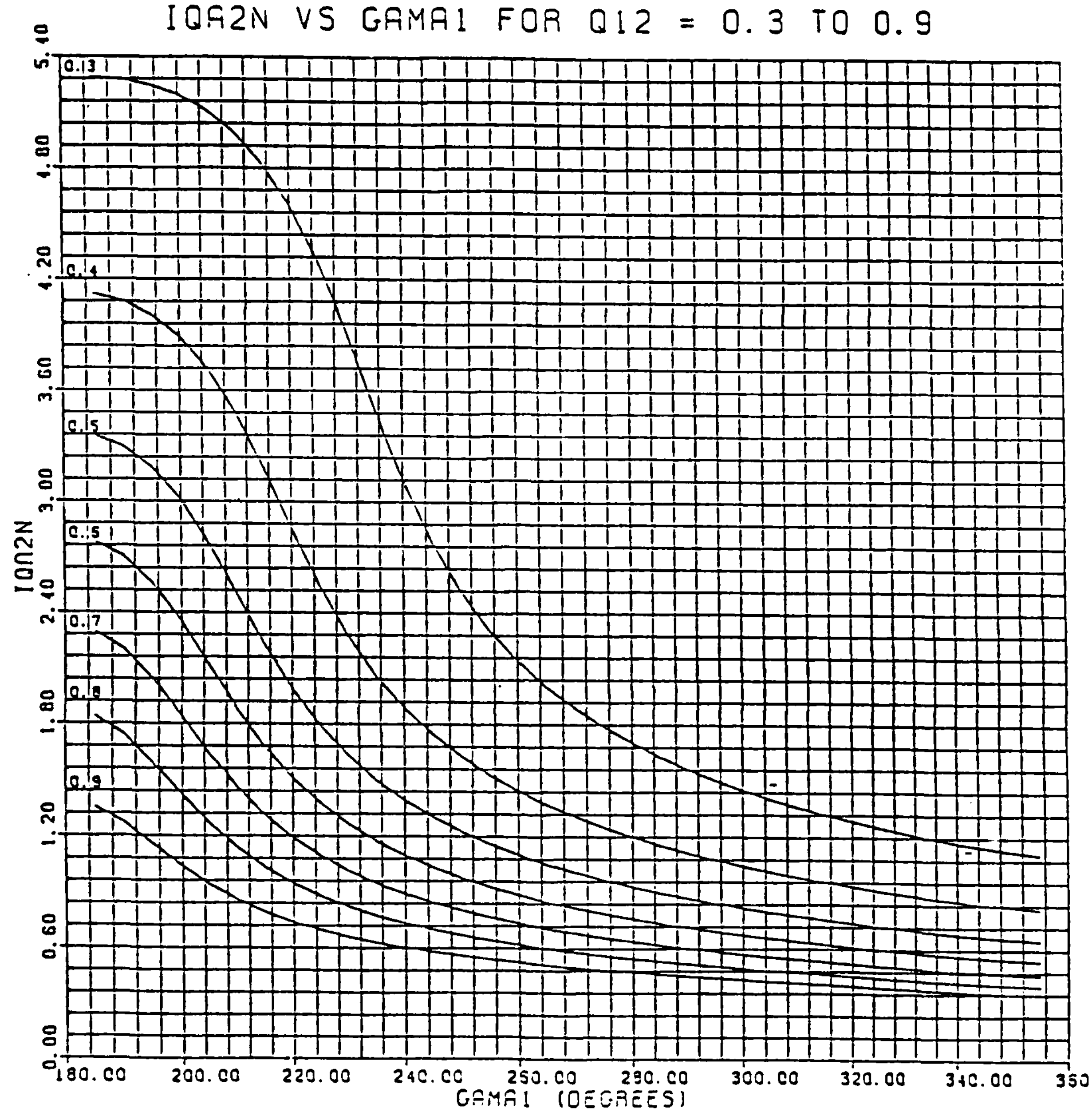


Figure 2.12: Single Phase Cascaded Schwarz Converter, IQA2N vs. GAMMA1. Curves are parametric for Q12 = 0.3 to 0.9.

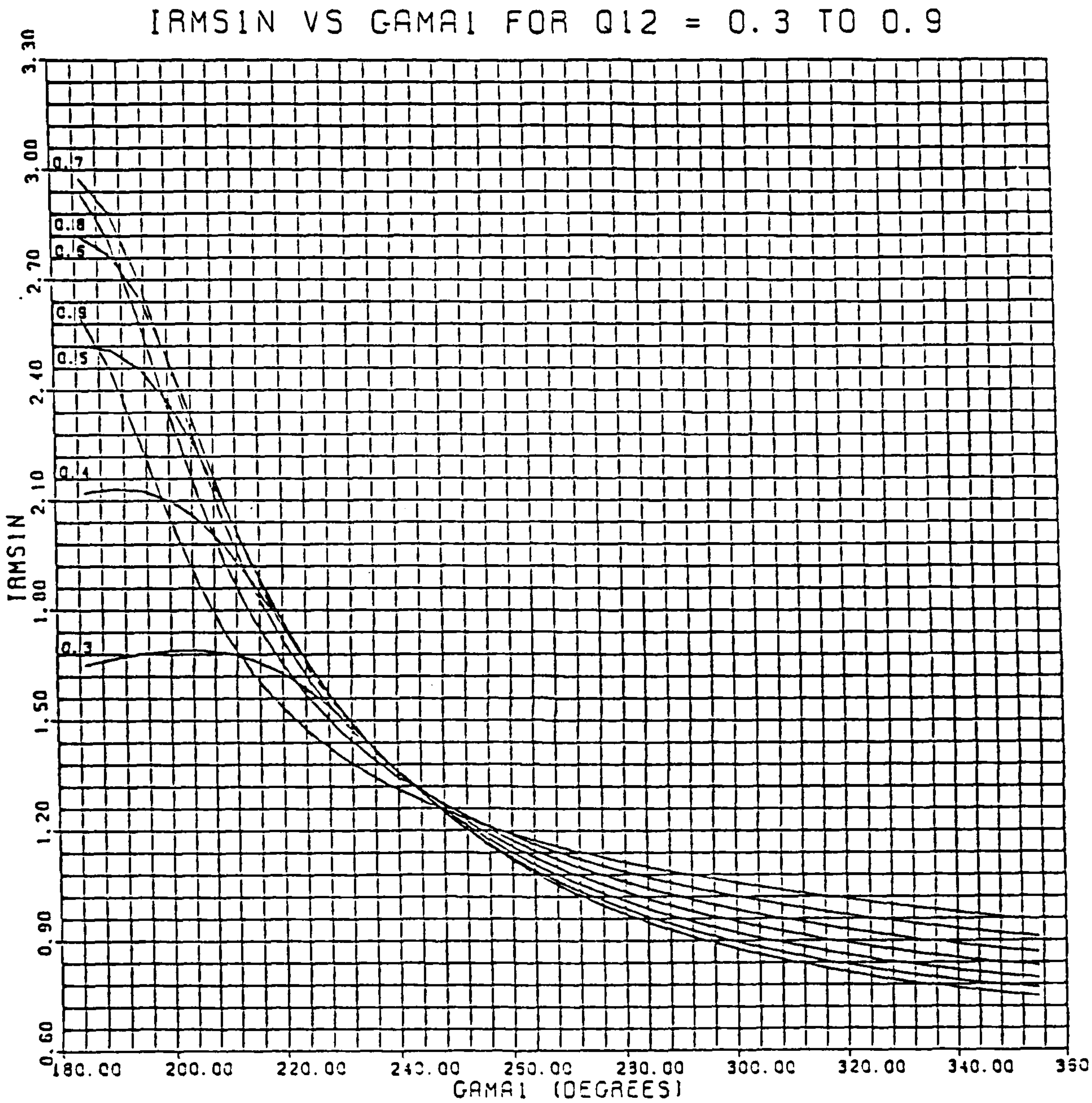


Figure 2.13: Single Phase Cascaded Schwarz Converter, IRMS1N vs. GAMMA1. Curves are parametric for Q12 = 0.3 to 0.9.

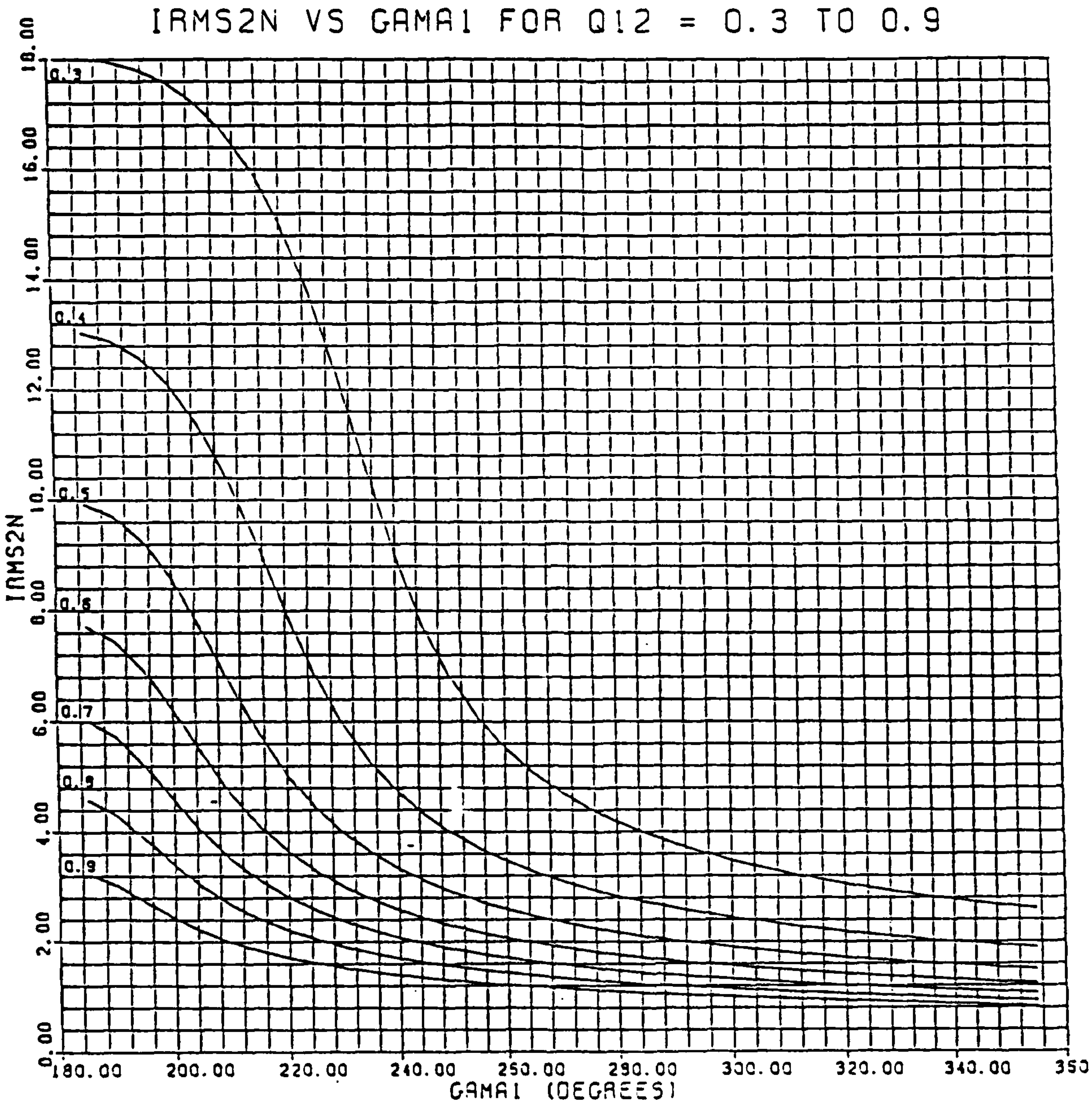


Figure 2.14: Single Phase Cascaded Schwarz Converter, IRMS2N vs. GAMMA1. Curves are parametric for Q12 = 0.3 to 0.9.

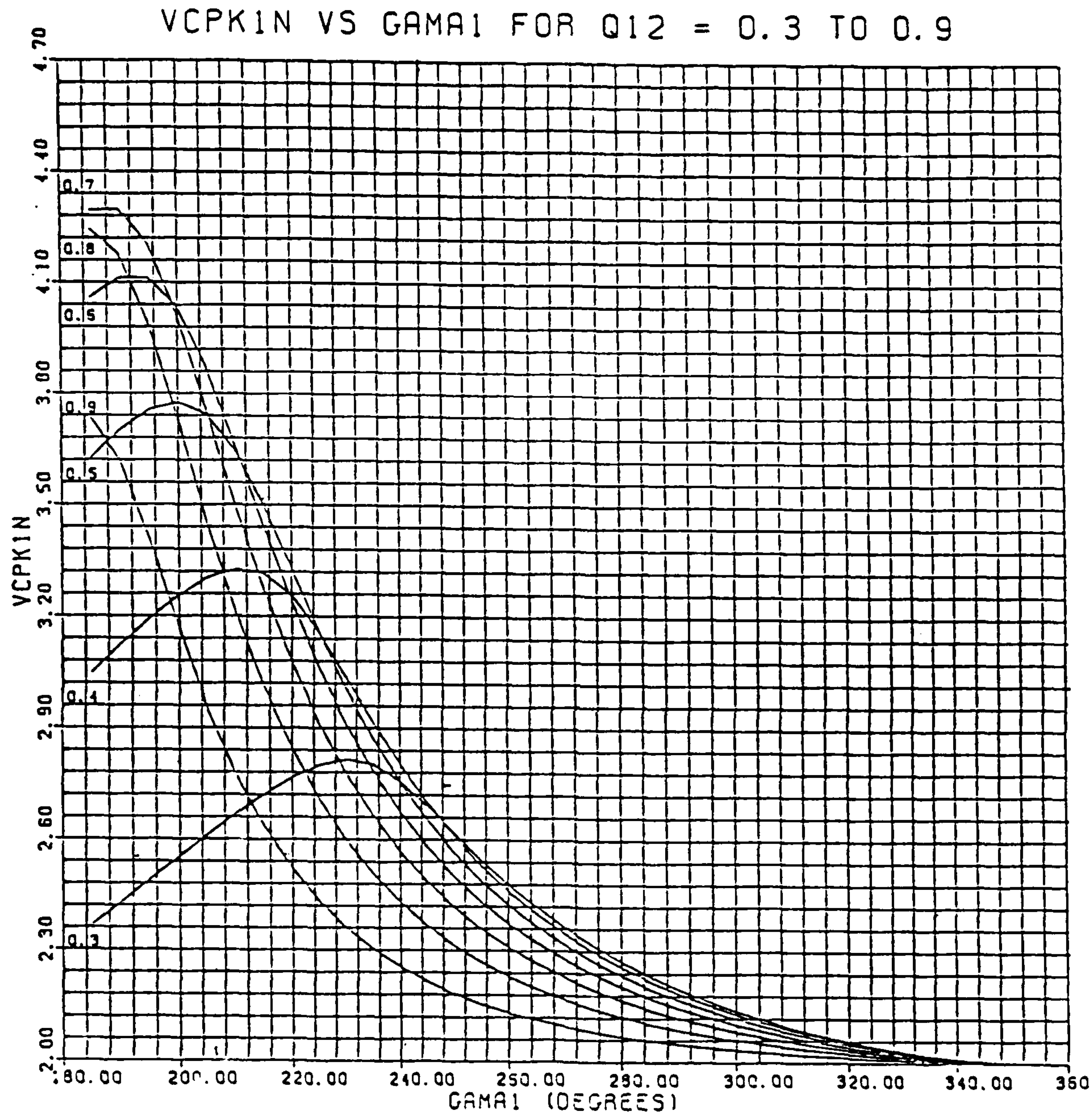


Figure 2.15: Single Phase Cascaded Schwarz Convertr, VCPK1N vs. GAMMA1. Curves are parametric for Q12 = 0.3 to 0.9.

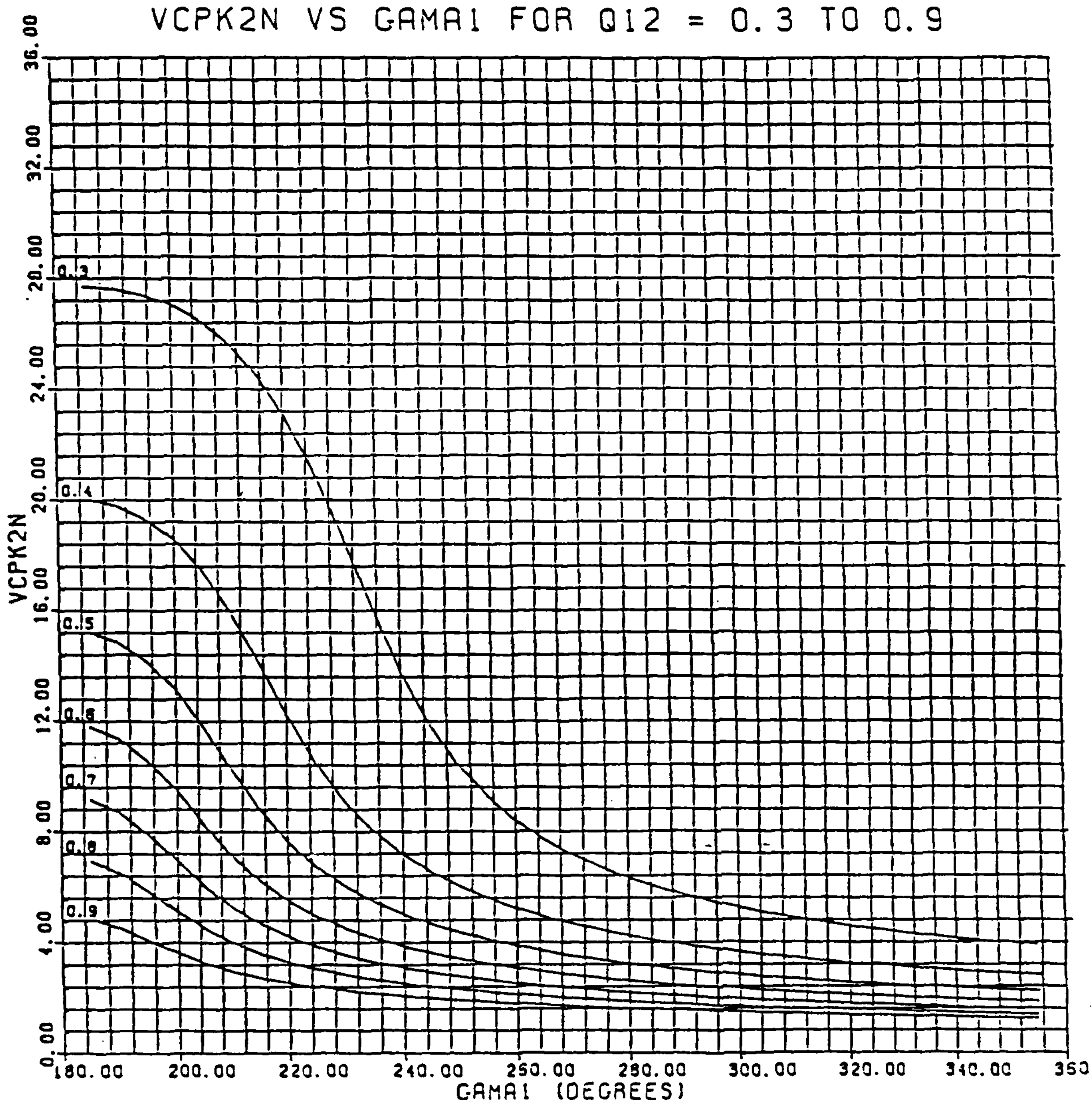


Figure 2.16: Single Phase Cascaded Schwarz Converter, VCPK2N vs. GAMMA1. Curves are parametric for Q12 = 0.3 to 0.9.

2.2 *Design Algorithm for the Single Phase Cascaded Schwarz Converter*

Equations (2.1) through (2.36) were used to develop a computer algorithm to provide a means to design a cascaded Schwarz converter circuit. This program, its documentation and an example run is presented in Appendix D.

The program of Appendix D was designed to determine the size of the resonant components and the operating characteristics of the cascaded Schwarz converter at the steady-state full load operating point. Figure 2.1 shows the basic block diagram of the cascaded Schwarz converter. The following variables are the known quantities to be supplied to the program at execution time:

1. VS1 = dc input voltage to stage 1.
2. VO2 = dc output voltage of stage 2.
3. IA2 - dc output current of stage 2.
4. FO1 = the resonant frequency of stage 1.
5. FO2 = the resonant frequency of stage 2.
6. FS1MAX = the maximum operating frequency of stage 1.
7. FS2 = the fixed operating frequency of stage 2.
8. K12 = the ratio of the characteristic impedance of stage 1 to the characteriscic impendance of stage 2.
9. NU1 = the efficiency of stage 1.
10. NU2 - the efficiency of stage 2.
11. N1 = the transformer turns ratio of stage 1.
12. N2 = the transformer turns ratio of stage 2.

In order to compensate for the inefficiency of each stage, a voltage drop is included at the input to stage 1 and the output of stage 2 as shown in Figure 2.17. The design algorithm computes the effective input voltage to stage 1 by solving the following equation:

$$V_{S1\,EFF} = V_{S1} NU_1 \tag{2.37}$$

where NU_1 is the efficiency of stage 1. Likewise the effective output voltage of stage 2 is determined by

$$V_{O2\,EFF} = \frac{V_{O2}}{NU2} . \tag{2.38}$$

After the above calculations are completed, the block diagram with the inefficiency effects taken into account is shown in Figure 2.18.

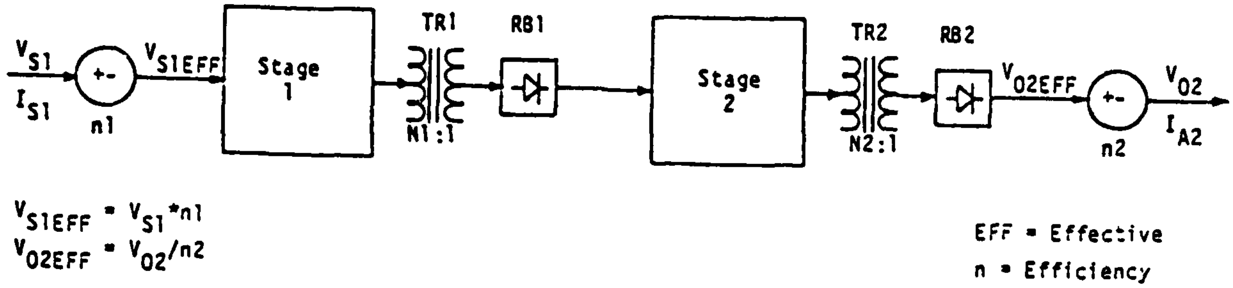


Figure 2.17: Cascaded Schwarz Converter Block Diagram with Lumped Inefficiency

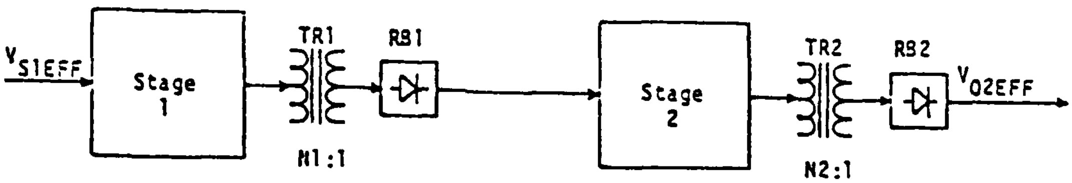


Figure 2.18: Single Phase Cascaded Schwarz Converter with the Inefficiency Taken into Account.

If the isolation transformers have a turns ratio other than one-to-one, then their effect must also be accounted for in the design algorithm. The procedure for accounting for the stage 1 transformer turns ratio is to reflect the appropriate electrical variables of stage 1 to the secondary side of the transformer. The equations used to do this are as follows:

$$V_{S1R} = \frac{V_{S1EFF}}{N1}, \quad k_{12R} = \frac{k_{12}}{N1^2} \tag{2.39}$$

where N1 is the stage 1 transformer turns ratio (N1 = primary/secondary) and V_{S1R} and K_{12R} are the reflected values of V_{S1EFF} and K_{12} respectively. The variable k_{12} is the ratio of the characteristic impedance of stage 1 to the characteristic impedance of stage 2. Likewise, the appropriate variables of stage 2 are reflected to the primary side of the stage 2 transformer by the following equations:

$$V_{O2R} = V_{O2EFF}N2, \quad I_{O2R} = \frac{I_{O2}}{N2} \tag{2.40}$$

where N2 is the stage 2 transformer turns ratio (N2 = primary/secondary) and V02R and I02R are the reflected values of V02EFF, the effective outut voltage of stage 2, and I02, the average output current of stage 2, respectively. Figure 2.19 shows the block diagram of the cascaded Schwarz converter with the effects of the transformer turns ratios taken into account. The final block diagram used in the design algorithm is shown in Figure 2.20. Figure 2.20 includes the appropriate control variables used and the effects of the stage inefficiencies and transformer turns ratios.

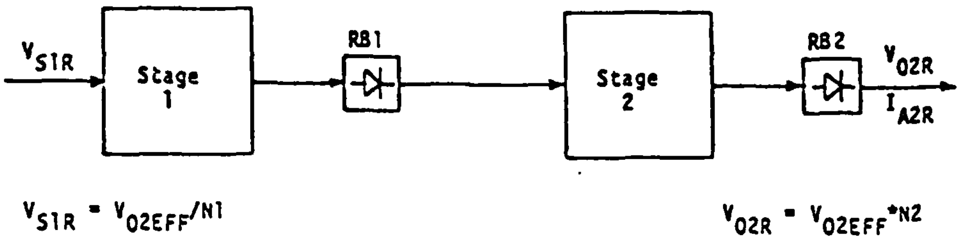


Figure 2.19: Cascaded Schwarz Converter with Transformer Turns Ratios Taken into Account.

Once the input data is given, the program determines the known quantities, q12, γ_1 and γ_2 and estimates the initial conditions of the unknown quantities, q1, α_1 and α_2. Then the equations of Table 1 are solved numerically to find the final values for q1, q2, α_1 and α_2. This

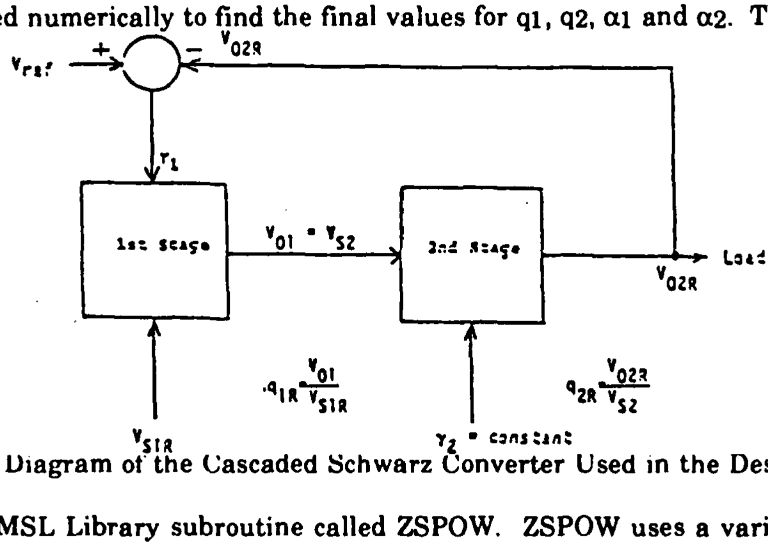


Figure 2.20: Block Diagram of the Cascaded Schwarz Converter Used in the Design Algorithm.

program uses an IMSL Library subroutine called ZSPOW. ZSPOW uses a variation of Newton's method for solving simultaneous nonlinear equations. Upon determining the values of the unknown variables of Table 1, equations (2.17) through (2.36) can be solved to determine the operating characteristics of the cascaded Schwarz converter.

Using the value of IA2N from equation (2.27), the values of the resonant components for stage 2 can be determined from the following,

$$I_{B2} = \frac{V_{02}}{Z_{02}} = \frac{I_{A2}}{I_{A2N}} \tag{2.41}$$

or

$$Z_{02} = V_{02}\frac{I_{A2N}}{I_{A2}} \tag{2.42}$$

and

$$\omega_{02} = 2\pi f_{02} = \frac{1}{\sqrt{L_2 C_2}} . \tag{2.43}$$

Then, rearranging equations (2.2) and (2.43) gives

$$C_2 = \frac{L_2}{Z_{02}^2} \tag{2.44}$$

and

$$L_2 = \frac{1}{\omega_{02}^2 C_2} . \tag{2.45}$$

Substituting equation (2.45) into equation (2.44) gives,

$$C_2 = \frac{1}{\omega_{02} Z_{02}} . \tag{2.46}$$

Finally, L_2 can be determined by rearranging equation (2.44) as

$$L_2 = C_2 Z_{02}^2 . \tag{2.47}$$

To determine the resonant compenents of stage 1, the following equations are used,

$$Z_{01} = k_{12} Z_{02} \tag{2.48}$$

where k_{12} is a known parameter and Z_{02} is determined by equation (2.42) and

$$\omega_{01} = 2\pi f_{01} = \frac{1}{\sqrt{L_1 C_1}} . \tag{2.49}$$

Then using equations (2.2), (248) and (2.49) and following the same procedure as outlined in equations (2.44) through (2.47), the following equations can be determined,

$$C_1 = \frac{1}{\sqrt{\omega_{01} Z_{01}}} \tag{2.50}$$

and

$$L_1 = C_1 Z_{01}^2 \,. \tag{2.51}$$

A flow chart for the computer design algorithm is presented in Figure 2.21. A computer run for a 900-watt cascaded Schwarz converter circuit is presented in Figure 2.22. This computer run makes use of experimental results given in reference [14] for a 900-watt single phase cascaded Schwarz converter. The following data were taken from reference [14]:

$V_{S1} = 240$ Vdc, $V_{02} = 197$ Vdc, $I_{02} = 3.9$ Vdc,

$N1 = 1.0$, $N2 = 1.0$, $NU1 = 0.954$, $NU2 = 0954$, $K_{12} = 0.48$,

$f_{01} = 19{,}230.0$ Hz, $f_{02} = 21{,}500.0$ Hz $\gamma_1 = 256°$, $\gamma_2 = 195°$,

$f_{S1MAX} = 180° \dfrac{f_{01}}{\gamma_1} = 13{,}521.0$ Hz, $f_{S2} = 180° \dfrac{f_{02}}{\gamma_2} = 19.846.0$ Hz.

The actual values of the resonant components used in the circuit were,

$C_1 = 0.153\ \mu F$, $C_2 = 0.0662\ \mu F$, $L_1 = 464.6\ \mu H$, $L_2 = 852.6\ \mu H$.

These resonant component values were compared with the values obtained from the computer algorithm and the results are summarized in Table 2. The results show the values obtained from the computer algorithm are in good agreement with the values of the components used in the actual circuit.

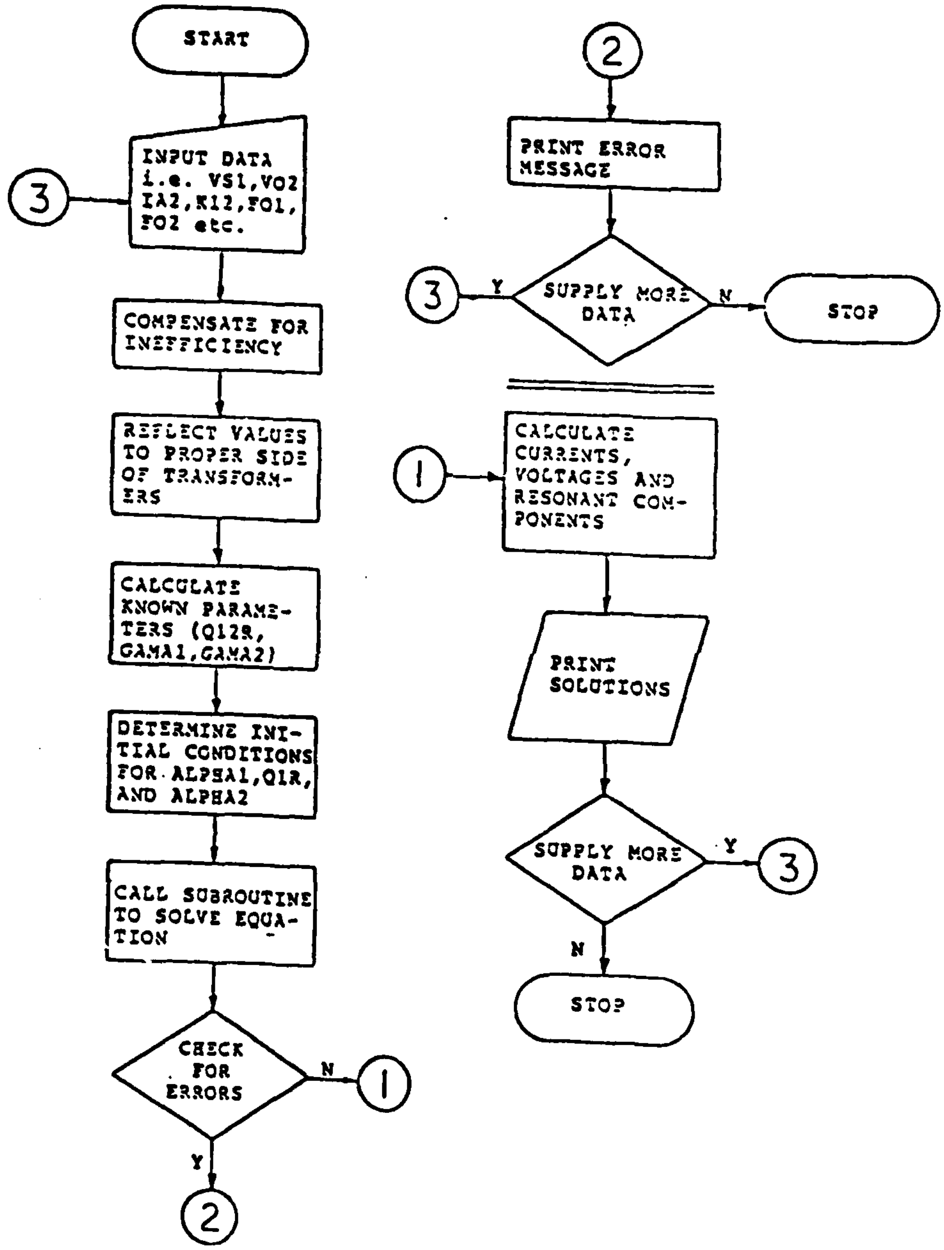


Figure 2.21: Flow Chart of the Design Algorithm for the Single Phase Parallel Module Cascaded Schwarz Converter.

```
This program determines the currents, voltages, transistor
commutation times and the resonant component values for
the Single Phase Cascaded Schwarz Converters.  The user
is required to input the following data at execution time

    VS1 = The input voltage to stage one.
    VO2 = The output voltage of stage two.
    IA2 = The average output current of stage two.
    N1  = Stage one transformer turns ratio (N1/N2).
    N2  = Stage two transformer turns ratio (N1/N2).
    NU1 = Stage one efficiency.
    NU2 = Stage two efficiency.
    K12 = The ratio of the characteristic impedance of
          stage one to the characteristic impedance of
          stage two.
    FO1 = The resonant frequency of stage one.
    FS1MAX = The maximum operating frequency of stage one.
    FO2 = The resonant frequency of stage two.
    FS2 = The fixed operating frequency of stage two.


(*) VS1 (in volts D.C.) = >>>>>240.0
(*) VO2 (in volts D.C.) = >>>>>197.0
(*) IA2 (in amps D.C.) = >>>>>>3.9
(*) N1 (ratio in decimal) = >>>1.0
(*) N2 (ratio in decimal) = >>>1.0
(*) NU1 (in decimal) = >>>>>>>>0.954
(*) NU2 (in decimal) = >>>>>>>>0.954
(*) K12 (in decimal) = >>>>>>>>0.48
(*) FO1 (in Hertz) = >>>>>>>>>>19230.0
(*) FS1MAX (in Hertz) = >>>>>>>13521.0
(*) FO2 (in Hertz) = >>>>>>>>>>21500.0
(*) FS2 (in Hertz) = >>>>>>>>>>19846.0
```

IA1 (amps)	IDA1 (amps)	IPK1 (amps)	IQA1 (amps)	IRMS1 (amps)	VCPK1 (volts)
3.691	0.043	8.059	1.802	4.782	474.57

IA2R (amps)	IDA2 (amps)	IPK2 (amps)	IQA2 (amps)	IRMS2 (amps)	VCPK2 (volts)
3.900	0.052	6.539	1.898	4.449	795.67

C1 (farads)	L1 (henrys)	ZO1 (ohms)	C2 (farads)	L2 (henrys)	ZO2 (ohms)
0.1438E-06	0.4763E-03	0.5755E-02	0.6174E-07	0.8875E-03	0.1199E-03

ALPHA1 (deg)	ALPHA2 (deg)	T1Q (sec)	T2Q (sec)	GAMMA1 (deg)	GAMMA2 (deg)
79.34	27.72	0.1146E-04	0.3581E-05	256.00	195.00

Q1R	Q2R	Q12R	VO1R
0.9529	0.9465	0.9019	218.1705

Figure 2.22: Computer Run for a 900-watt Cascaded Schwarz Converter.

Table 2: 900-watt Cascaded Schwarz Converter Design Program Results

First Stage		Second Stage	
Resonant Capacitor		Resonant Capacitor	
Actual	Calculated	Actual	Calculated
0.153 μF	0.146 μF	0.0662 μF	0.0626 μF
% difference = 4.6%		% difference = 5.4%	
Resonant Inductor		Resonant Inductor	
Actual	Calculated	Actual	Calculated
464.6 μH	486.0 μH	852.6 μH	902.2 μH
% difference = 4.6%		% difference = 5.8%	

2.3 *Second Stage Parallel Module Design*

The actual single phase cascaded Schwarz converter studied in this thesis is designed with a second stage consisting of three parallel Schwarz converters. Note, as stated previously three Schwarz inverters were used in the second stage to provide a system that would produce almost the same maximum output power as the three phase system. The previous design algorithm must therefore be modified to account for this change. Figure 2.23 shows a general block diagram of the single phase parallel module cascaded Schwarz converter.

Given the idealizations shown in Figure 2.17 through Figure 2.19, the second stage of the parallel module design can be reduced to an equivalent circuit consisting of a single Schwarz converter. An equivalent resonant impedance can be obtained by computing the parallel combination of the resonant impedances of each module. To assure equal load sharing between the parallel modules, it will be assumed that the resonant impedance of the three modules are equal. The resonant impedance of the equivalent circuit will then be equal to one-third the size

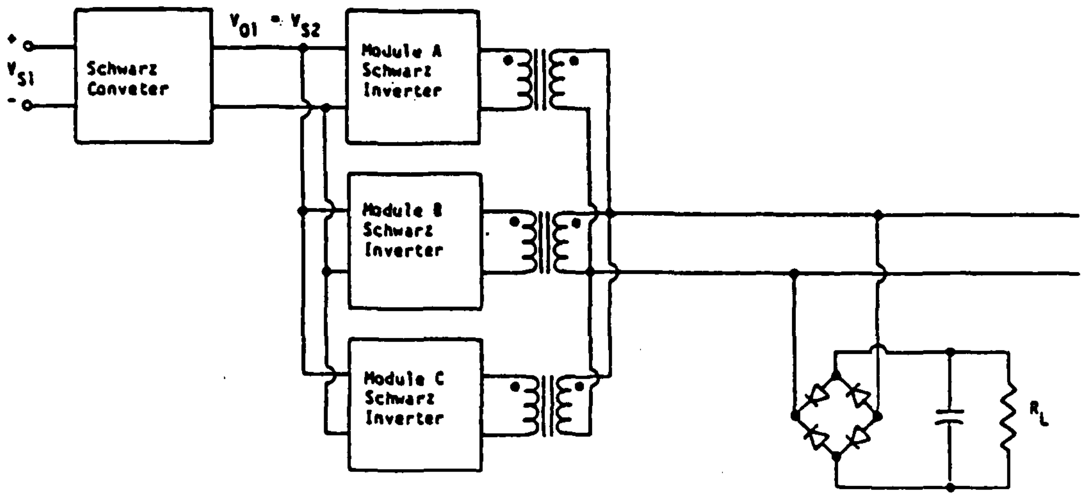


Figure 2.23: General Block Diagram of the Single Phase Parallel Module Cascaded Schwarz Converter

of the individual module resonant impedance. Likewise, the resonant capacitor and inductor of the equivalent circuit will be three times and one-third the size of the module resonant capacitor and inductor, respectively.

The revised program for the single phase parallel module cascaded Schwarz converter can be found in Appendix E. Note that using parallel modules does not change the other input variables, such as the resonant and operating frequencies, input and output voltages, and the output current to the program.

This design program was run using the following data for a 2500-watt single phase parallel module cascaded Schwarz converter which will be discussed later.

$V_{S1} = 112$ Vdc, $V_{02} = 203$ Vdc, $I_{02} = 12.56$ Adc,

$N1 = 0.4$, $N2 = 1.0$, $NU1 = 0.957$, $NU2 = 0.922$, $K_{12} = 0.154$,

$f_{01} = 20{,}833.0$ Hz, $f_{02} = 20{,}408.0$ Hz, $\gamma_1 = 204°$, $\gamma_2 = 202°$,

$$F_{S1MAX} = 180° \frac{f_{01}}{\gamma_1} = 18{,}382.0 \text{ Hz}, \quad F_{S2} = 180° \frac{f_{02}}{\gamma_2} = 18.182.0 \text{ Hz}.$$

Figure 2.24 shows the computer run for the 2500-watt single phase parallel module cascaded Schwarz converter. The actual values of the resonant components used in the circuit were,

$C_1 = 1.24$ μF, $L_1 = 53.0$ μH, $C_{2a,b,c} = 0.0652$ μF, $L_{2a,b,c} = 1.04$ mH.

```
This program determines the currents, voltages, transistor
commutation times and the resonant component values for
the Single Phase Parallel Module Cascaded Schwarz
Converter.  The user is required to input the following
data at execution time

     VS1 = The input voltage to stage one.
     VO2 = The output voltage of stage two.
     IA2 = The average output current of stage two.
     N1  = Stage one transformer turns ratio (N1/N2).
     N2  = Stage two transformer turns ratio (N1/N2).
     NU1 = Stage one efficiency.
     NU2 = Stage two efficiency.
     K12 = The ratio of the characteristic impedance of
           stage one to the equivalent characteristc
           impedance of stage two.
     FO1 = The resonant frequency of stage one.
     FS1MAX = The maximum operating frequency of stage one.
     FO2 = The resonant frequency of stage two.
     FS2 = The fixed operating frequency of stage two.


 (*) VS1 (in volts D.C.) = >>>>>112.0
 (*) VO2 (in volts D.C.) = >>>>>203.0.
 (*) IA2 (in amps D.C.) = >>>>>>12.25
 (*) N1 (ratio in decimal) = >>0.4
 (*) N2 (ratio in decimal) = >>1.0
 (*) NU1 (in decimal) = >>>>>>>0.958
 (*) NU2 (in decimal) = >>>>>>>0.921
 (*) K12 (in decimal) = >>>>>>>>0.154
 (*) FO1 (in Hertz) = >>>>>>>>>>20833.0
 (*) FS1MAX (in Hertz) = >>>>>>>18182.0
 (*) FO2 (in Hertz) = >>>>>>>>>>20408.0
 (*) FS2 (in Hertz) = >>>>>>>>>>18182.0


          *** STAGE ONE VALUES ***

 IA1 (amps)  IDA1 (amps)  IPK1 (amps)  IQA1 (amps)  IRMS1 (amps)   VCPK1 (volts)
  27.204       0.494        47.731       13.107        16.932          310.26

 C1 (farads)  L1 (henrys)   ZO1 (ohms)  GAMMA1 (degrees)  ALPHA1 (degrees)
  0.1206E-05   0.4841E-04   0.6337E-01      206.24             38.86

 T1Q (secs)      Q1R        Q12R     VO1R (volts)
  0.8141E-05  0.9273      0.8217        248.74


          *** STAGE TWO EQUIVALENT CIRCUIT VALUES ***

 IA2 (amps)  IDA2 (amps)  IPK2 (amps)  IQA2 (amps)  IRMS2 (amps)   VCPK2 (volts)
  12.280       0.350        20.963        5.790        14.056          890.90

 C2EQ (farads)  L2EQ (henrys)  ZO2EQ (ohms)  GAMMA2 (degrees)  ALPHA2 (degrees)
  0.1895E-06     0.3209E-03     0.4115E-02       202.04             40.58

 T2Q (secs)      Q2R
  0.5524E-06  0.8861


          *** STAGE TWO INDIVIDUAL MODULE VALUES ***

 IDA2M (amps)  IPK2M (amps)  IQA2M (amps)  IRMS2M (amps)   VCPK2 (volts)
    0.117         6.988         1.930          4.686          890.90

 C2M (farads)   L2M (henrys)   ZO2M (ohms)   GAMMA2 (degrees)  ALPHA2 (degrees)
  0.5686E-06     0.1070E-03     0.1234E-03       202.04             40.58

 DO YOU WISH TO INPUT MORE DATA? Y=1/N=2
 2
 FORTRAN STOP
```

Figure 2.24: Computer Run for a 2500-watt Single Phase Parallel Module Cascaded Schwarz Converter.

Table 3: **Results of the Design Program for a 2500-watt Single Phase Parallel Module Cascaded Schwarz Converter.**

First Stage		Second Stage	
Resonant Capacitor		Resonant Capacitor	
Actual	Calculated	Actual	Calculated
1.240 μF	1.200 μF	0.0652 μF	0.0626 μF
% difference = 3.6%		% difference = 7.8%	
Resonant Inductor		Resonant Inductor	
Actual	Calculated	Actual	Calculated
53.00 μH	48.85 μH	1.040 μH	0.972 μH
% difference = 4.0%		% difference = 6.6%	

These resonant component values were compared with the values obtained from the computer algorithm and the results are summarized in Table 3.

2.4 Three Phase Cascaded Schwarz Converter Design Procedure

At the present time, a steady-state model for the three phase cascaded Schwarz converter has not been determined. However, by assuming that the power level of the three phase system is equal to that of the single phase parallel module system, the design algorithm for the single phase parallel module cascaded Schwarz converter can be used in the design of the three phase system.

Experimental results indicate that if a single phase a a three phase wye system are to have the same output voltages, the turns ratios of their transformers should be related approximately as follows,

$$\frac{N_p}{N_s}\,(3\text{ phase}) \approx 2 \cdot \frac{N_p}{N_s}\,(1\text{ phase}).$$

This can be explained as follows. Figure 2.25 shows a model for the single phase system where the input and output are well defined square wave voltage sources. At full load i_o is very close to a sinewave, indicating that the fundamental components of v_s and v_o are approximately related as follows,

$$\overline{V}_{01} = \overline{V}_{S1} - \overline{Z}_{01}\overline{I}_{01}$$

where $|\overline{V}_{S1}| = \frac{4}{\pi} V_S$ and $\overline{Z}_{01} = j\left(\omega L_0 - \frac{1}{\omega C_0}\right)$. At full load (or close to resonance) $|\overline{Z}_{01}\overline{I}_{01}|$ is quite small, so that,

$$V_{01} \sim V_{S1} = \frac{4}{\pi} V_S .$$

Also

$$V_{01} = \frac{4}{\pi} V_0 ,$$

therefore

$$V_O \sim V_S.$$

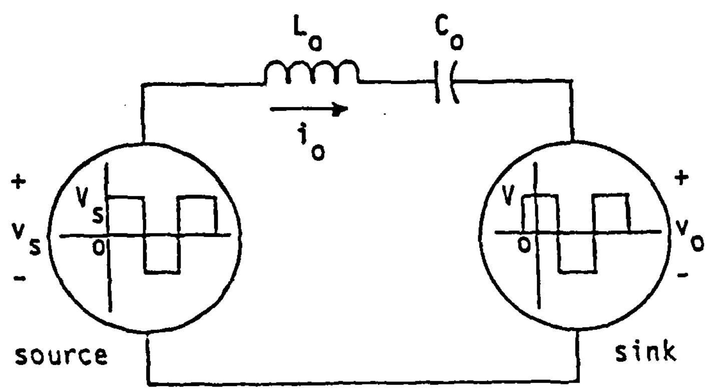


Figure 2.25: Approximate Model for a Single Phase System with a Rectified Load.

Figure 2.26 shows a model for the three phase system where the inputs are three well defined square wave voltage sources with 120-degree relative phase shifts, and the line-to-line outputs are three well defined 3-step voltage sources also with 120-degree relative phase shifts. One of these waveforms is shown in greater detail in Figure 2.27. At full load (or close to resonance), we have for the "ab" fundamental components

$$\overline{V'_{01}} = \overline{V}_{S_{a1}} - \overline{V}_{S_{b1}} - \overline{Z}_{01}\overline{I}_{a1} + \overline{Z}_{01}\overline{I}_{b1}$$

where

$$\overline{V}_{S_{a1}} = \frac{4}{\pi} V'_S \quad \angle 0°,$$

$$\overline{V}_{Sb1} = \frac{4}{\pi} V'_S \quad \angle{-120^\circ}$$

and

$$|\overline{V}_{Sa1} - \overline{V}_{Sb1}| = \frac{4\sqrt{3}}{\pi} V'_S.$$

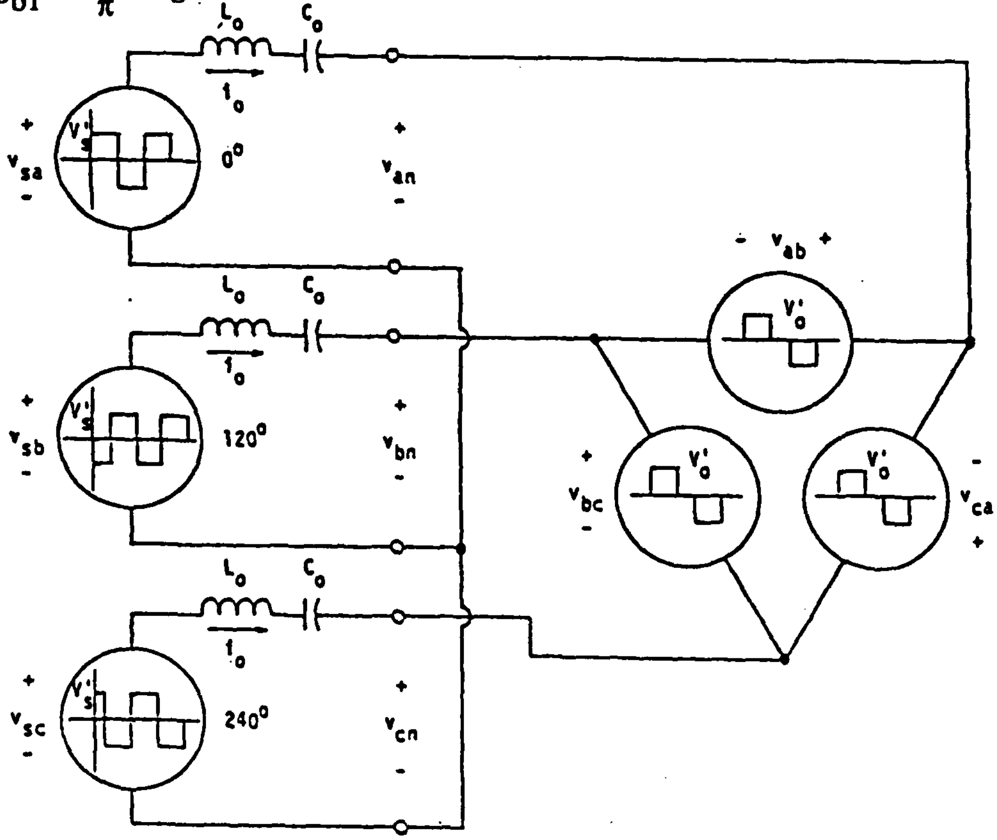


Figure 2.26: Approximate Model for a Three Phase System with a Rectified Load.

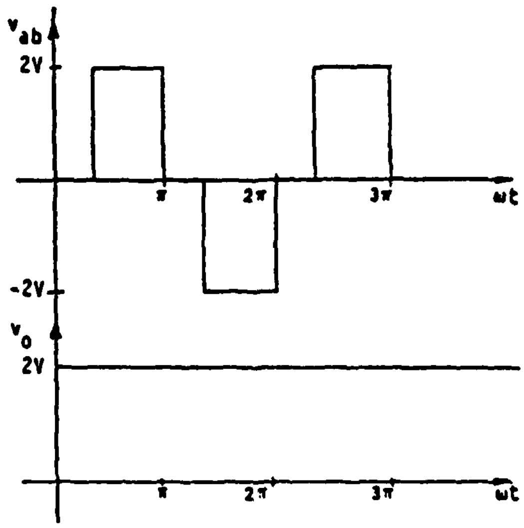


Figure 2.27: Line-to-Line and Rectified Output Voltages for the Three Phase System.

At full load, $\left|\overline{Z}_{01}(\overline{I}_{a1} - \overline{I}_{b1})\right|$ is quite small so that,

$$V'_{01} \approx \frac{4\sqrt{3}}{\pi} V'_S .$$

Also

$$V'_{01} = \frac{4}{\pi} \left(\frac{\sqrt{3}}{2} V'_0\right)$$

therefore

$$V'_0 \approx 2V'_S.$$

For the rectified values of the two systems to be equal we need,

$$V_0 = V'_0$$

or

$$V_S = 2V'_S .$$

Therefore the winding ratios must be related as indicated earlier.

It should be noted that the previous three phase analysis placed no constraint on the v_{an}, v_{bn} and v_{cn} waveforms. Because of the voltage drops across the L_o C_o impedance and the lack of triplen harmonic components, these waveforms are not well defined such as those in Figure 2.28, but they will have a very distorted waveform as shown in Figure 2.29.

The assumption of the power levels being equal for the three phase and single phase parallel module system will be verified in the next section. Experimental results showing the load sharing between the inverters of the second stage of the three phase system will be compared with those of the single phase parallel module system to prove or disprove this assumption.

2.5 Cable Weights for Single Phase and Multiphase Systems.

For an n-phase system, the transmission line is composed of n-conductors assuming that a ground wire is not used. To compare an n-phase system with a single phase system, assume that the two transmission lines have equal line-to-neutral voltages, equal volt-ampere ratings, and equal losses. Then by equating the volt-ampere (VA) rating of the two systems we have,

$$VA_n = VA_1 \tag{2.52}$$

or

$$nV_LI_n = V_LI_1 \tag{2.53}$$

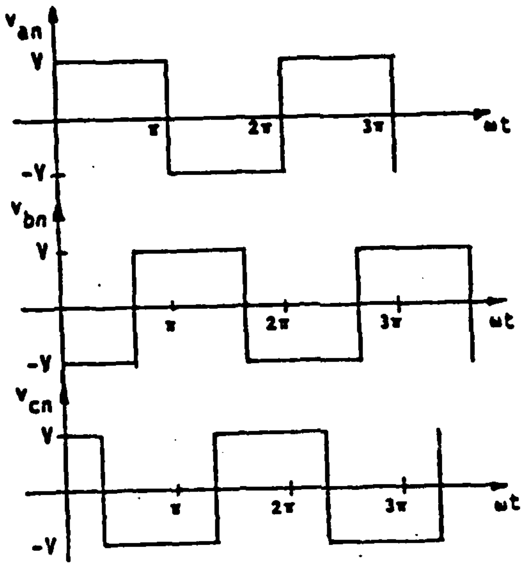
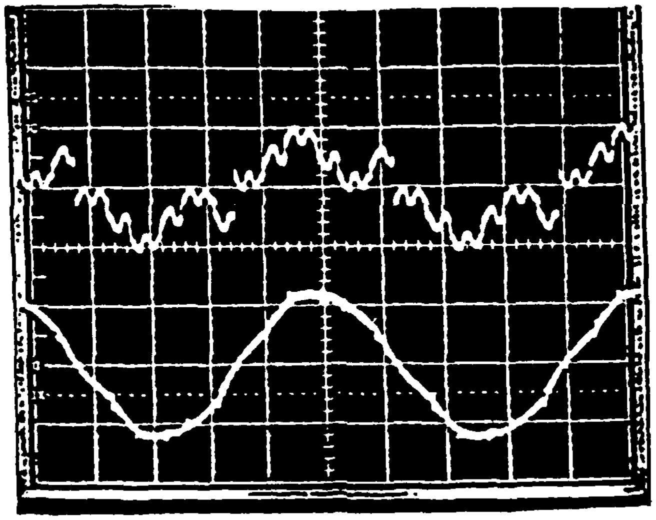


Figure 2.28: Output Voltages for Three Independent Converters with 120-Degree Relative Phase Shifts.



Top - V_m	200 V/div
Bot - i_a	10 A/div
V_{S1} = 112 Vdc	V_{C2} = 202 Vdc
I_{S1} = 24.66 Adc	I_{C2} = 12.16 Adc

Figure 2.29: Line-to-Neutral Voltage and Line Current for the Three Phase System.

or

$$nV_L I_n = V_L I_1 \tag{2.53}$$

where n is equal to the number of phases, VA_n is the volt-amp rating of the n-phase system, VA_1 is the volt-amp rating of the single phase system, V_L is the line-to-neutral voltage, I_n is the current of phase n and I_1 is the current of the single phase system. Solving equation (2.53) for I_n gives,

$$I_n = \frac{I_1}{n}. \tag{2.54}$$

For equal losses we have,

$$P_{L_n} = P_{L_1} \tag{2.55}$$

or

$$nI_n^2 R_n = I_1^2(2R_1) \tag{2.56}$$

where P_{L_n} is the power losses of the n-phase system, P_{L_1} is the power losses of the single phase system, R_n is the resistance of the n^{th} conductor of the n-phase system and R_1 is the conductor resistance of the single phase system. Substituting equation (2.54) into equation (2.56) gives,

$$\frac{I_1^2}{n} R_n = 2R_1 I_1^2 \tag{2.57}$$

or

$$R_n = 2nR_1 \tag{2.58}$$

The resistances of equation (2.58) can be defined as,

$$R_n = \frac{\rho l}{A_n} \text{ and } R_1 = \frac{\rho l}{A_1} \tag{2.59}$$

where ρ is the resistivity of the conductor material, A_n is the cross-ectional area for the conductor of the n-phase system, A_1 is the cross-sectional area for the single phase conductor and l is the length of the conductor which is the same for both systems. Substituting equation (2.59) into equation (2.58) and letting $k_1 = \rho l$ gives,

$$\frac{k_1}{A_n} = 2n\frac{k_1}{A_1} \tag{2.60}$$

or

$$A_1 = 2nA_n. \tag{2.61}$$

The copper weight for the single phase system is

$$wt_1 = 2(\delta l A_1) \tag{2.62}$$

and for an n-phase system we have

$$wt_n = n(\delta l A_n) \tag{2.63}$$

where δ is the density of the conductor material and l is the length of the conductor. Substituting equation (2.61) into equation (2.63) gives,

$$wt_n = \frac{nk_2A_1}{2n} = \frac{k_2A_1}{2} \tag{2.64}$$

where $k_2 - \delta l$. Finally, substituting equation (2.62) into equation (2.64) gives

$$wt_n = \frac{wt_1}{4}\,. \tag{2.65}$$

Therefore, for an n-phase transmission system without a ground wire, the copper weight is independent of the number of phases for $n \geq 2$ as long as the losses are constant for a given volt-ampere rating. Note, a single phase system can be considered a two phase system without a ground wire where the line-to-line voltage is twice the line-to-neutral voltage as shown in Figure 2.30. This means that a single phase system, with one side above neutral and one below, will have the same copper weight as a multiphase system if the line-to-neutral voltages are the same. This same conclusion has been drawn in earlier references such as reference [17].

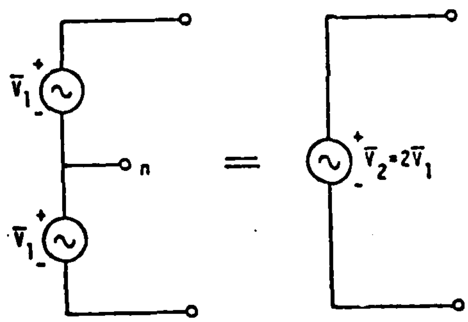


Figure 2.30: Equivalence Between Single and Two Phase Systems.

2.6 *Design of the Filter Capacitors.*

The design of the filter capacitors is dependent upon the amount of current ripple the capacitor must sink. This determines the capacitor heating since the power dissipated is equal to $I^2_{ripple}R$, where R is the equivalent series resistance of the capacitor.

A full wave, rectified, single phase current waveform is shown in Figure 2.31. This current waveform is a sine-wave approximation to the rectified output current of the Schwarz converter. It is commonly assumed that the total ac component (ripple) contained in the waveform must be sunk by the input or output filter capacitors. This is a good assumption since the impedance of these capacitors is usually quite low when compared to the other shunt impedances.

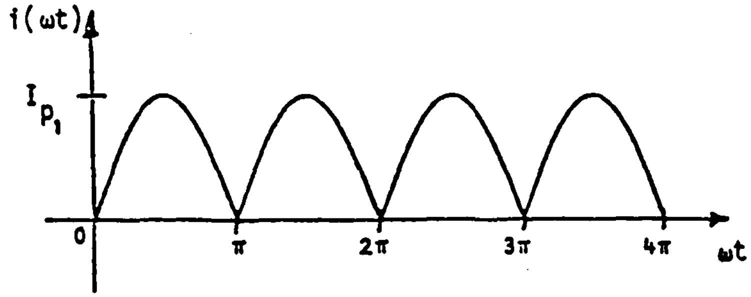


Figure 2.31: Approximate Rectified Output Current Waveform.

The ripple current can be determined by calculating the average current, I_{avg}, and the rms current I_{rms}, of the waveform shown in Figure 2.31. The equation for the average current is,

$$I_{avg_1} = \frac{1}{\pi}\int_0^{\pi} I_{p_1} \sin(\omega t)\, d\omega t. \qquad (2.66)$$

Performing the integration gives,

$$I_{avg_1} = \frac{2}{\pi} I_{p_1} \qquad (2.67)$$

The equation used to determine the rms current is,

$$I_{rms_1} = \left[\frac{1}{\pi}\int_0^{\pi} [I_{p_1} \sin(\omega t)]^2\, d\omega t\right]^{\frac{1}{2}}. \qquad (2.68)$$

Performing the integration gives,

$$I_{rms_1} = \frac{I_{p_1}}{\sqrt{2}}. \qquad (2.69)$$

The equation for the ripple current is,

$$I_{ripple_1} = \sqrt{I^2 rms_1 - I^2 avg_1}\ . \qquad (2.70)$$

Substituting equation (2.67) and equation (2.69) into equation (2.70) gives,

$$I_{ripple_1} = \sqrt{\frac{I^2 p_1}{2} - \frac{4 I^2 p_1}{\pi^2}} \qquad (2.71)$$

or after simplification

$$I_{ripple_1} = 0.3078 I_{p_1} \,. \tag{2.72}$$

A similar equation can be derived for the full wave, rectified, three phase current waveform. This current waveform is shown in Figure 2.32.

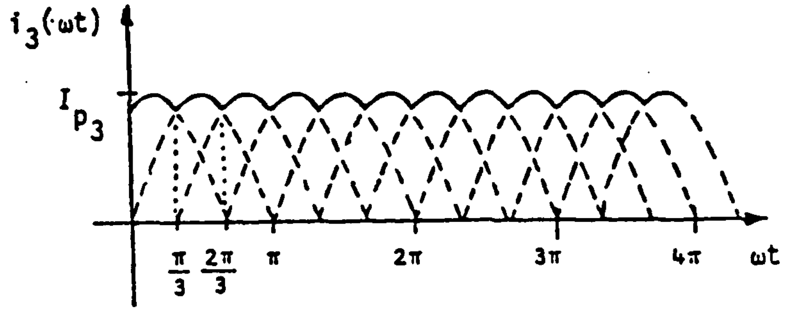


Figure 2.32: Rectified Three Phase Current Waveform

The equation for the average current is,

$$I_{avg_3} = \frac{3}{\pi} \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} I_{p_3} \sin(\omega t)\, d\omega t. \tag{2.73}$$

Performing the integration gives,

$$I_{avg_3} = \frac{3}{\pi} I_{p_3} \,. \tag{2.74}$$

The equation used to determine the rms current is,

$$I_{rms_3} = \left[\frac{3}{\pi} \int_{\frac{\pi}{3}}^{\frac{2\pi}{3}} [I_{p_3} \sin \omega t]^2 \, d\omega t \right]^{\frac{1}{2}} \tag{2.75}$$

Performing the integration gives,

$$I_{rms_3} = 0.9558 I_{p_3} \tag{2.76}$$

The ripple current can be determined by substituting equaton (2.74) and equation (2.76) into equation (2.70) which gives,

$$I_{ripple_3} = 0.0401 I_{p_3} \tag{2.77}$$

The ripple current ratings for the output filter of the second stage of the single phase and three phase cascaded Schwarz converter can be determined directly from equations (2.72) and (2.77) respectively. The output filter of the first stage, which is also the input filter to the second stage, can be determined from the model shown in Figure 2.33, where I_1 and I_2 are the output currents of stages 1 and 2 respectively.

The output current of the stage 1 can be described by the following equation,

$$I_{S1} = I_{1O} + I_{1R} \tag{2.78}$$

where I_{1O} is the average current and I_{1R} is the ripple current. Similarly, the input current of stage 2 is,

$$I_{S2} = I_{2O} + I_{2R} \tag{2.79}$$

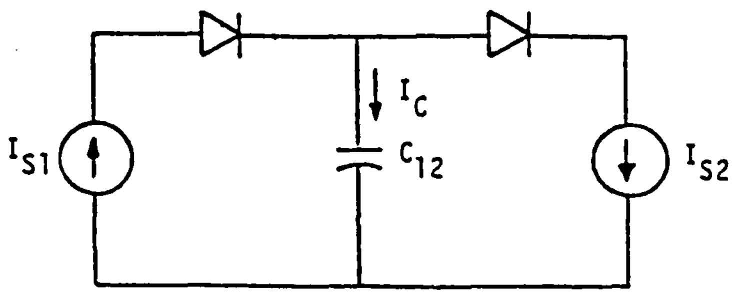


Figure 2.33: Model for Determining the Output Filter Capacitor of Stage 1.

Since $I_{1O} = I_{2O}$, the RMS current in the capacitor, C_{12}, is

$$I_C = \sqrt{I_{1R}^2 + I_{2R}^2} \tag{2.80}$$

where I_{1R} and I_{2R} are determined from equation (2.72) for the single phase cascaded Schwarz converter and from equations (2.72) and (2.77) for the three phase cascaded Schwarz converter. Note that I_{1R} and I_{2R} do not add directly because the frequencies of the current waveforms are not equal.

The reduction in the amount of ripple current for the three phase system versus the single phase system can be determined by equating the average current of each system. There-fore, setting equation (2.67) equal to equation (2.74) we have,

$$I_{p_1} = \frac{3}{2} I_{p_3} . \tag{2.81}$$

Substituting equation (2.81) into equation (2.72) gives,

$$I_{ripple_1} = 0.46 I_{p_3} \tag{2.82}$$

or

$$I_{p_3} = 2.17 I_{ripple_1} \tag{2.83}$$

Substituting equation (2.83) into equation (2.77) gives,

$$I_{ripple_1} = 11.51 I_{ripple_3} . \tag{2.84}$$

Therefore, as shown by the above derivation the ripple current for the single phase system is 11.51 times larger than the ripple current of the three phase system for $I_{avg_1} = I_{avg_3}$.

Section III

EXPERIMENTAL RESULTS FOR PART I

3.1 Single Phase Parallel Module Cascaded Schwarz Converter.

A series of tests were performed on the single phase parallel module cascaded Schwarz converter. The output of the second stage was connected directly to a rectified load (i.e., no transmission cable was present between the second stage transformer and the load rectifier). Figure 3.1 shows the locations for the various measured voltages and currents. Since the voltage inputs and outputs of the first and second stages are dc, dc voltage and current measure-ments were used to find the average power. The dc input and output voltages were measured with digital dc voltmeters. The dc input and output currents of the first and second stages were determined by using meter shunts and measuring the voltage drop across the shunts with digital dc voltmeters. All of the meters and shunts were calibrated before the tests and the corrections were included in the readings.

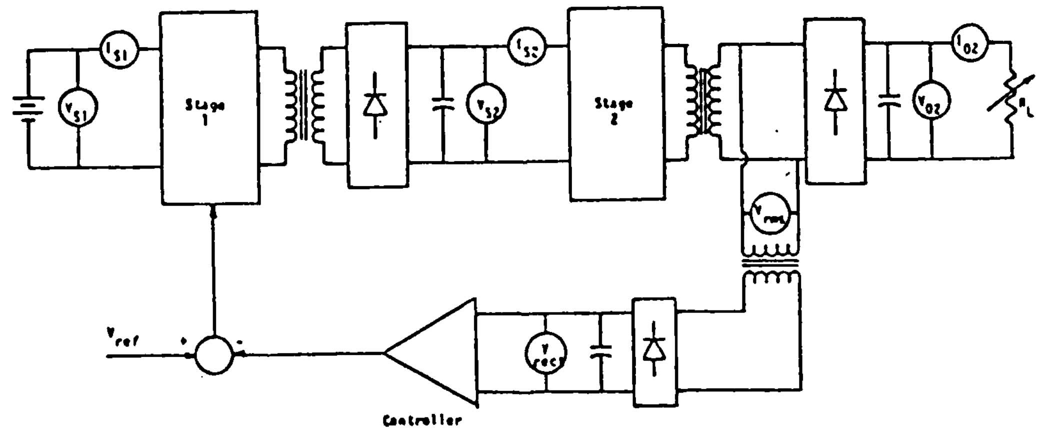


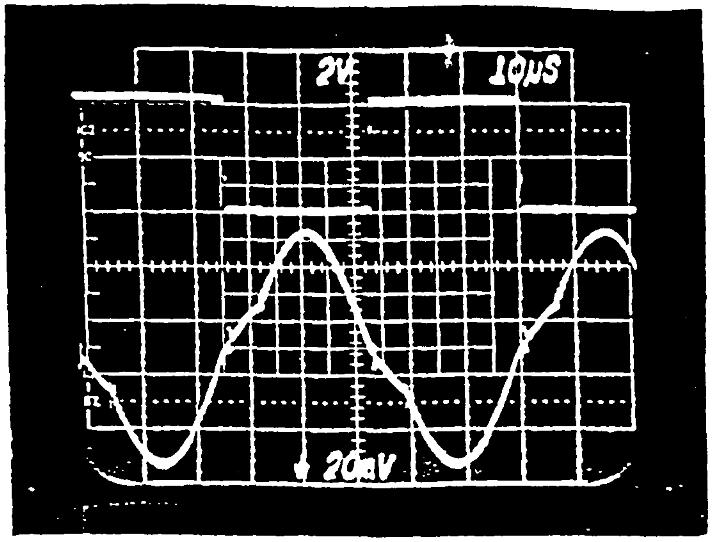
Figure 3.1: Test Locations for the SPPM Cascaded Schwarz Converter.

Output voltage and current waveforms for full load and no-load conditions are shown in Figure 3.2 and Figure 3.3 respectively. Figure 3.4 shows the no-load output voltage and the current in the recycling rectifier. The recycling rectifier circuit is shown in Figure A.9 of Appendix A. Under very light loading conditions, the output voltage from the second stage contains an under-damped transient. This transient will cause the output filter capacitor to peak charge, and its voltage rating or the voltage rating of the rectifier diodes may be exceeded. Figure 3.5 shows the output voltage, v_{02} on the ac bus and the input voltage V_{S2} for the second stage Schwarz inverters during a light load condition with the recycling rectifier disconnected. During this test the output voltage, V_{02} rose to 230 Vdc for V_{S1} equal to 112 Vdc. Figure 3.6 shows the same loading condition with the recycling rectifier circuit operating. With the recycling rectifier operating and V_{S1} equal to 112 Vdc, the output voltage V_{02} was 210 Vdc. During a light load condition, the peak voltage is greater than the input voltage for the second stage. This causes the recycling rectifier to be forward biased and the energy from the under-damped transients is recycled back into the input of the second stage. Thus, the recycling rectifier prevents the over-charging of the output filter capacitor and keeps the no-load output voltage approximately equal to the full load output voltage. It should be noted that for loading conditions other than very light loads, the recycling rectifier is reversed biased because the input voltage, V_{S2} is greater than the output voltage, V_{02}.

The load sharing between the individual inverters of the second stage is presented in Figure 3.7. Figure 3.7 shows the current in the resonant inductor of each inverter at full load. As shown, the currents are very well matched for the three inverters of the second stage.

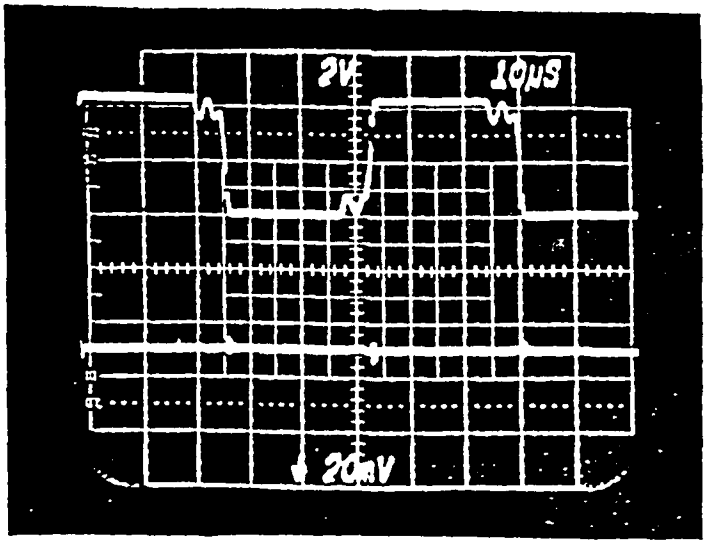
The effects of the size of the output filter capacitors are shown in Figure 3.8 through 3.12. These figures show that the dominant voltage ripple frequency is two times larger than the operating frequency of the second stage. Also, a minimum value of 5.0-μF output filter capacitance is required to maintain a full load output voltage of 203 Vdc.

Table 4 summarizes the amount of peak-to-peak output ripple voltage for a given amount of output filter capacitance. This information will be used later in the output filter comparison between the single phase and three phase systems.



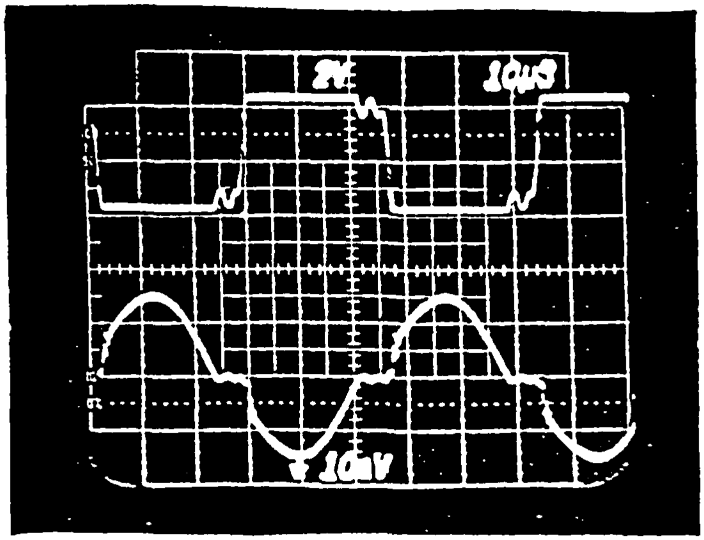
Top - v_{02}	200 V/div
Bot - i_{02}	10 A/div
V_{s1} = 112 Vdc	V_{02} = 203 Vdc
I_{S1} = 26 Adc	I_{02} = 12.09 Adc

Figure 3.2: Full Load Voltage and Current Waveforms for the SPPM Cascaded Schwarz Converter



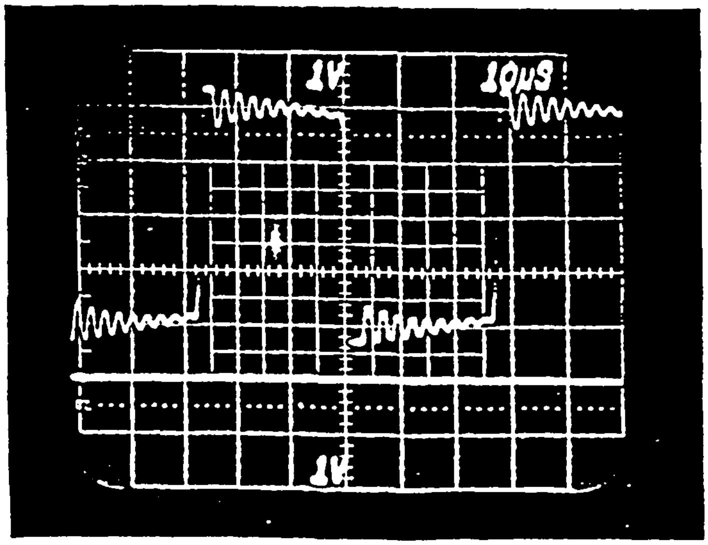
Top - v_{02}	200 V/div
Bot - i_{02}	10 A/div
V_{s1} = 112 Vdc	V_{02} = 209 Vdc
I_{S1} = 0.12 Adc	I_{02} = 0.0 Adc

Figure 3.3: No-Load Voltage and Current Waveforms for the SPPM Cascased Schwarz Converter



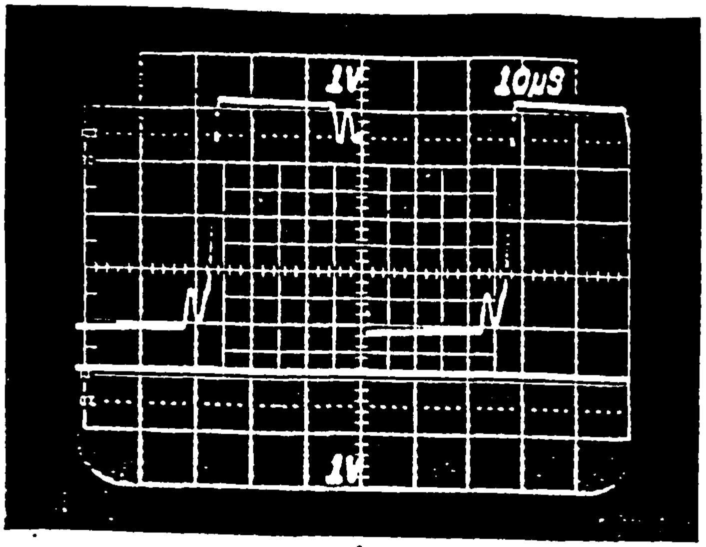
Top - v_{02}	200 V/div
Bot - $i_{recycle}$	0.5 A/div
V_{s1} = 112 Vdc	V_{02} = 210 Vdc
I_{S1} = 0.12 Adc	I_{02} = 0.0 Adc

Figure 3.4: No-Load Voltage and Recycling Rectifier Current Waveform for the SPPM Cascaded Schwarz Converter.



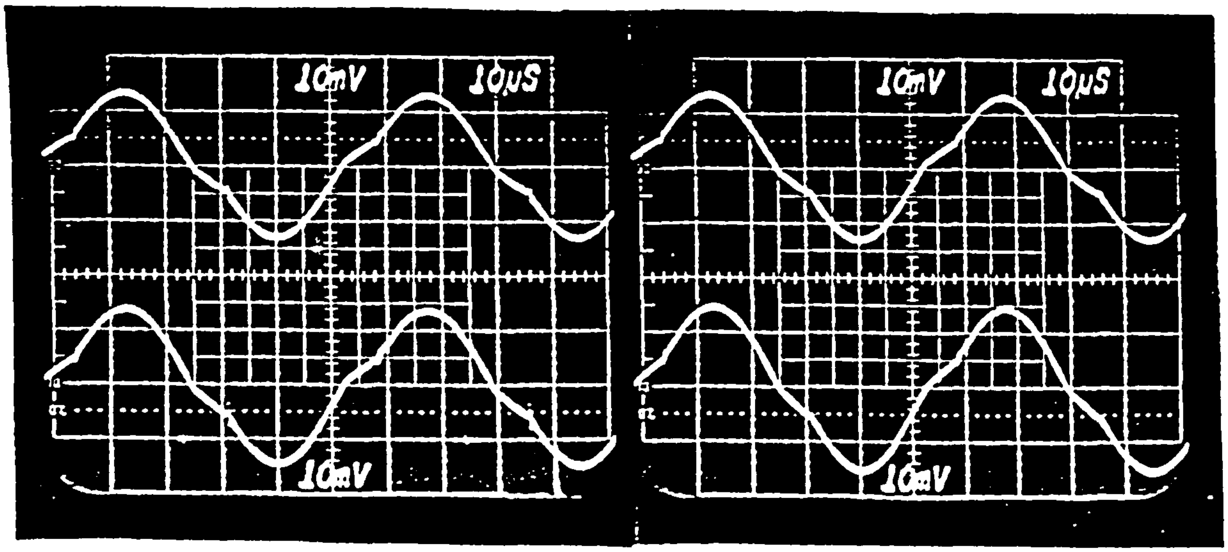
Top - v_{02}	200 V/div
Bot - V_{S2}	200 A/div
V_{S1} = 112 Vdc	V_{02} = 230 Vdc
I_{S1} = 0.09 Adc	I_{02} = 0.006 Adc

Figure 3.5: SPPM Cascaded Schwarz Converter Lightly Loaded without Recycling Rectifier.



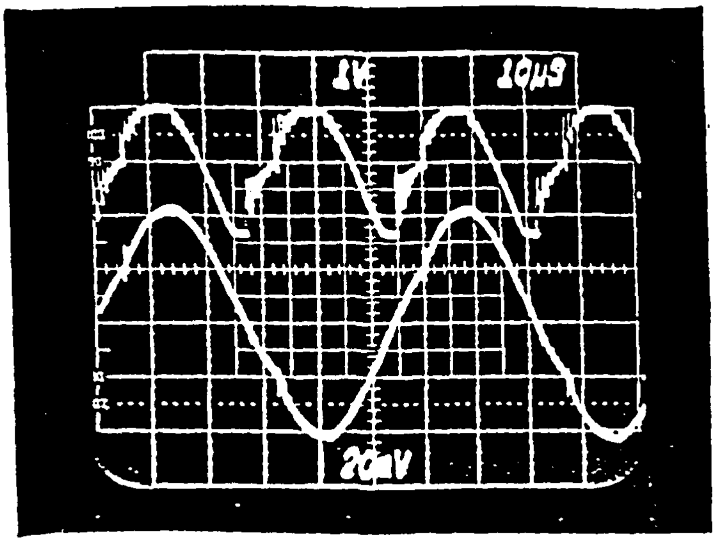
Top - v_{02}	200 V/div
Bot - V_{S2}	200 A/div
$V_{S1} = 112$ Vdc	$V_{02} = 210$ Vdc
$I_{S1} = 0.12$ Adc	$I_{02} = 0.005$ Adc

Figure 3.6: **SPPM Cascaded Schwarz Converter Lightly Loaded with Recycling Rectifier.**



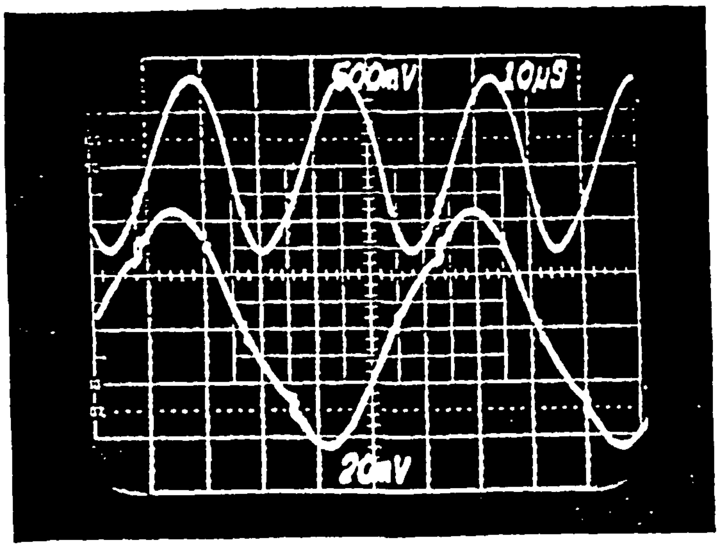
Top - $i_{a_{Lo}}$	5 A/div	Top - $i_{a_{Lo}}$	5 A/div
Bot - $i_{b_{Lo}}$	5 A/div	Bot - $i_{b_{Lo}}$	5 A/div
$V_{S1} = 112$ Vdc	$V_{02} = 203$ Vdc	$V_{S1} = 112$ Vdc	$V_{02} = 203$ Vdc
$I_{S1} = 26$ Adc	$I_{02} = 12.09$ Adc	$I_{S1} = 26$ Adc	$I_{02} = 12.09$ Adc

Figure 3.7: **SPPM Cascaded Schwarz Converter Current Sharing Waveforms.**



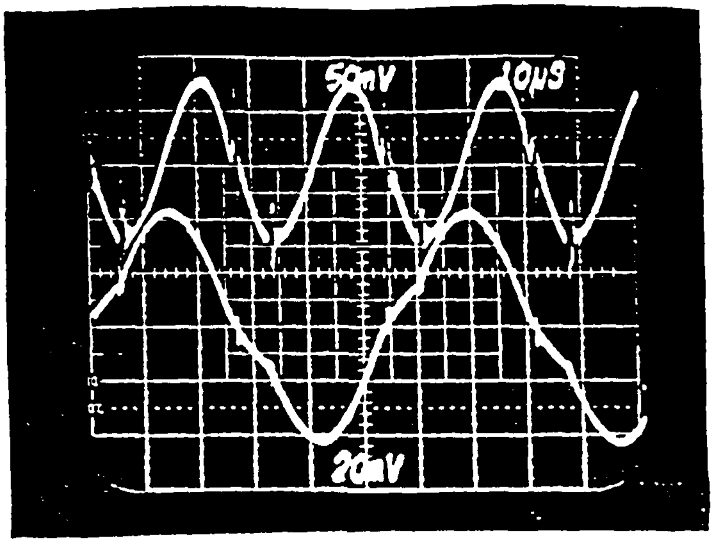
Top - V_{02} ripple 100 V/div
Bot - i_{02} 10 A/div
V_{S1} = 112 Vdc V_{02} = 131 Vdc
I_{S1} = 22 Adc I_{02} = 12.3 Adc

Figure 3.8: **SPPM Cascaded Schwarz Converter without an Output Filter Capacitor.**



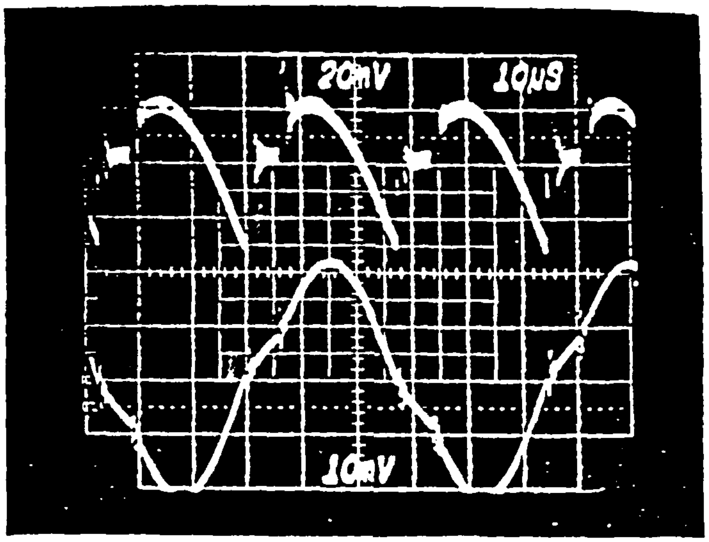
Top - V_{02} ripple 50 V/div
Bot - i_{02} 10 A/div
V_{S1} = 112 Vdc V_{02} = 113 Vdc
I_{S1} = 20 Adc I_{02} = 12.3 Adc

Figure 3.9: **SPPM Cascaded Schwarz Converter with a 0.5-μF Output Filter Capacitor.**



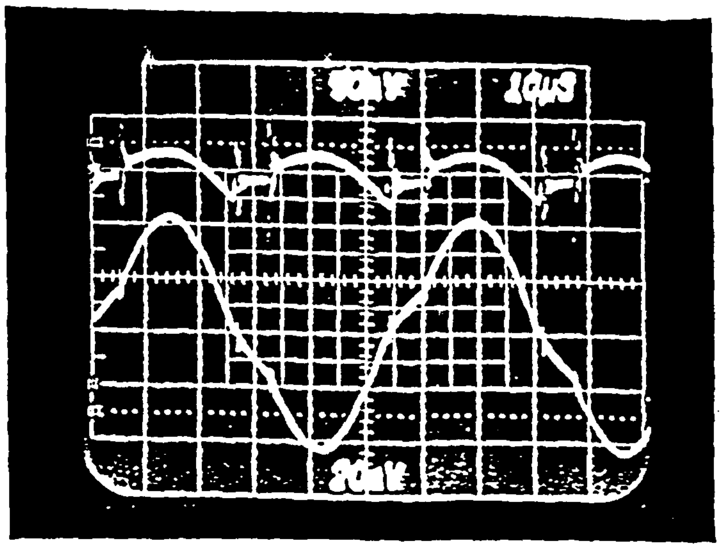
Top - V_{02} ripple 5 V/div
Bot - i_{02} 10 A/div
V_{S1} = 112 Vdc V_{02} = 203 Vdc
I_{S1} = 25.5 Adc I_{02} = 11.79 Adc

Figure 3.10: **SPPM Cascaded Schwarz Converter with a 5.0 μF Output Filter Capacitor.**



Top - v_{02} ripple 2 V/div
Bot - i_{02} 10 A/div
V_{S1} = 112 Vdc V_{02} = 202 Vdc
I_{S1} = 27 Adc I_{02} = 12.24 Adc

Figure 3.11: **SPPM Cascaded Schwarz Converter with a 100-μF Output Filter Capacitor.**



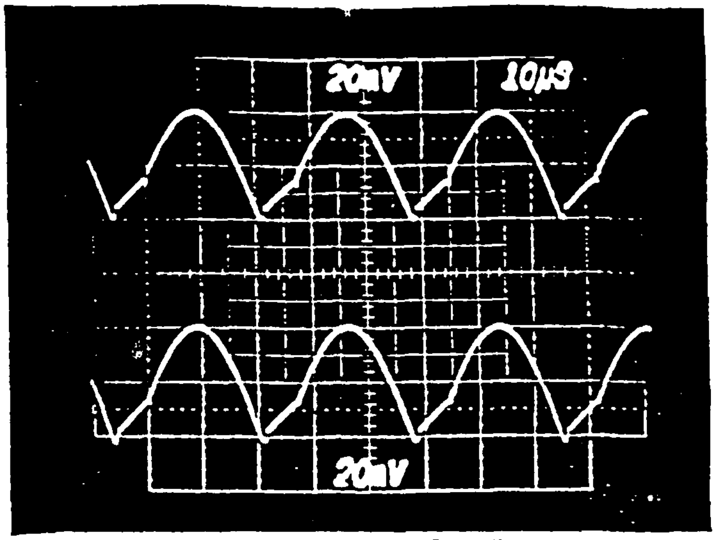
Top - v_{02}(ripple) 5 V/div
Bot - i_{02} 10 A/div
V_{S1} = 112 Vdc V_{02} = 202 Vdc
I_{S1} = 27 Adc I_{02} = 12.3 Adc

Figure 3.12: SPPM Cascaded Schwarz Converter with a 135-μF Output Filter Capacitor.

Table 4: SPPM Cascaded Schwarz Converter Filter Results

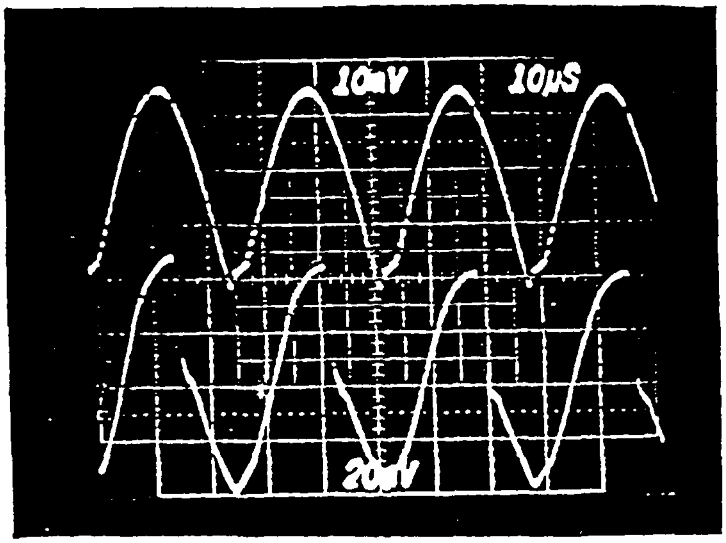
Capacitor (μF)	v_{02} - ripple (V_{p-p})	V_{02} (Vdc)	I_{02} (Adc)	V_{S1} (Vdc)	I_{S1} (Adc)
0.0	220	131	12.3	112	22
0.5	160	133	12.3	112	20
5.0	15	203	11.79	112	25.5
100	5.0	202	12.24	112	27
135	4.5	202	12.3	112	27

The amount of current ripple flowing in the input and output filter capacitors is shown in Figure 3.13 through Figure 3.15. Figure 3.13 shows the rectified output current of stage 2 and the ripple current flowing in the output filter capacitor. As shown in this figure, all of the ripple current is flowing into the filter capacitor. Figure 3.14 shows the rectified output current of stage 1 and the ripple current into the filter capacitor between stages 1 and 2. Figure 3.15 shows the input current of stage 2 and the ripple current into the filter capacitor between stages 1 and 2. The filter capacitor between stages 1 and 2 acts as an output filter for stage 1 and the input filter for stage 2. Therefore, this capacitor must be sized to handle the ripple currents from both stages.



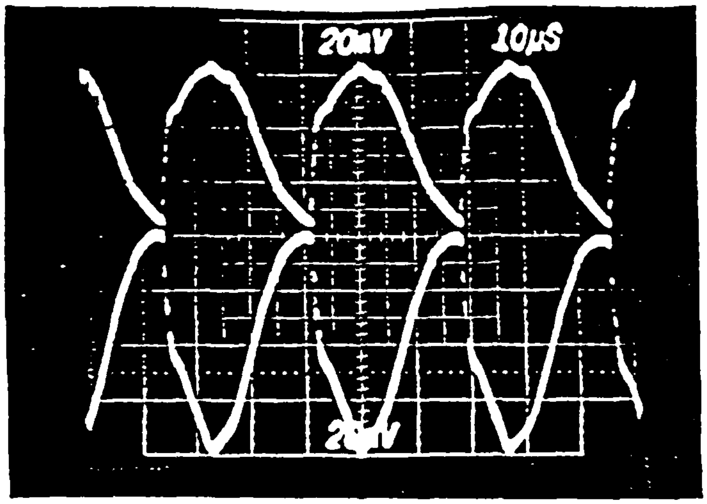
Top - i_{02}	10 A/div
Bot - $i_{c\text{-ripple}}$	10 A/div
V_{S1} = 112 Vdc	V_{02} = 203 Vdc
I_{S1} = 25 Adc	I_{02} = 12.2 Adc

Figure 3.13: Output Current Ripple from Stage 2 of the SPPM Cascaded Schwarz Converter with a 5.0-µF Filter Capacitor.



Top - i_{01} 5 A/div
Bot - $i_{c\ 12}$ 10 A/div
V_{S1} = 112 Vdc V_{02} = 203 Vdc
I_{S1} = 25.23 Adc I_{02} = 12.24 Adc

Figure 3.14: Rectified Output Current of Stage 1 and the Capacitor Ripple Current between Stages 1 and 2 of the SPPM Cascaded Schwarz Converter with a 270-µF Filter Capacitor.



Top - i_{S2} 10 A/div
Bot - $i_{c\ 12}$ 10 A/div
V_{S1} = 112 Vdc V_{02} = 203 Vdc
I_{S1} = 25.23 Adc I_{02} = 12.24 Adc

Figure 3.15: Input Current of Stage 2 and the Capacitor Ripple Current between Stages 1 and 2 of the SPPM Cascaded Schwarz Converter with a 270-mF Filter Capacitor.

Efficiency, short circuit and open circuit data are shown in Table 5. The average total efficiency for the given load range is 87.52%. The average stage 1 and stage 2 efficiencies over the given load range are 93.93% and 93.18% respectively. As exhibited by the data, the efficiencies change by only a few percent over the given load range. Note these efficiencies do not include the losses of the control circuits, but these losses are quite small because of the high input impedance of the transistor switching devices. Figure 3.16 shows graphically how the efficiency of eage stage and the overall system efficiency varies under conditions ranging from full load to ten percent of full load.

Table 5 shows that the output current I_{02} is limited to 13.28 Adc at short circuit. This is due to the current limiting circuit. There also exists an inherent current limiting characteristic associated with the use of the γ controller. This provides circuit protection immediately after a short circuit occurs and before the current limit has time to respond. The inherent current limiting characteristic of the γ controller is explained in reference [12]. Figure 3.17 shows the output voltage and current waveforms for the short circuit condition.

Percent load voltage regulation versus load current data are given in Table 6. The three different voltages measured for this test were the output voltage, V_{02}, the rms voltage V_{rms} at the sensing transformer primary (PTA of Figure A.9 in Appendix A) and the rectified output voltage, V_{rect}, from the voltage sensing transformer secondary. The voltages, V_{02} and V_{rms} are given to show how well they are being regulated. The actual voltage that is being regulated is V_{rect} which is derived from the "flat top" of the output line voltage. The percent voltage regulation for the output line, using V_{rect} as the control voltage, is 0.28% from full load to no-load. The percent voltage regulation using V_{02} and V_{rms} is 3.45% and 4.37% respectively.

Table 5: **SPPM Cascaded Schwarz Converter Efficiency, Short Circuit and Open Circuit Data.**

% Load	V_{S1}	I_{S1}	V_{S2}	I_{S2}	V_{02}	I_{02}
100%	112	25.8	263.9	10.48	203	12.56
90%	112	23.25	253.4	9.84	203	11.32
80%	112	20.64	243.3	90.4	203	10.04
70%	112	18.06	234.5	8.2	204	8.8
60%	112	15.45	226.7	7.28	204	7.54
50%	112	12.96	220.2	6.24	205	6.28
40%	112	10.53	215.2	5.12	205	5.04
30%	112	8.01	213.0	3.88	206	3.76
20%	112	5.34	211.9	2.60	207	2.52
10%	112	2.76	210.6	1.32	207	1.24
SC	112	1.77	175.9	1.0	0	13.28
OC	112	0.12	209.6	0.04	209	0

P_{IN1}	n_1	$P_{OUT1} = P_{IN2}$	n_2	P_{OUT2}	n_{TOT}
2889.6	95.71	2765.672	92.19	2549.68	88.24
2604.0	95.75	2493.456	92.16	2297.96	88.24
2311.68	95.14	2199.432	92.67	2038.12	88.17
2022.72	95.07	1922.9	93.36	1795.20	88.75
1730.4	95.38	1650.376	93.20	1538.16	88.89
1451.52	94.66	1374.048	93.69	1287.40	88.67
1179.36	93.43	1101.824	93.77	1033.20	87.61
897.12	92.12	826.44	93.72	774.56	86.33
598.08	92.12	550.94	94.68	521.64	87.22
309.12	89.93	277.992	92.33	256.68	83.03

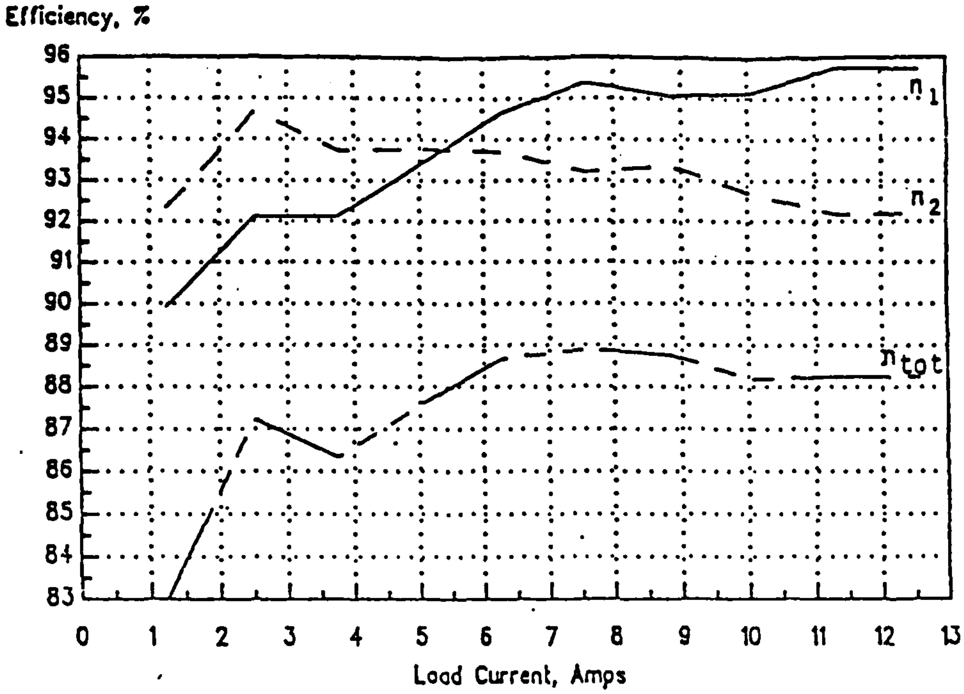
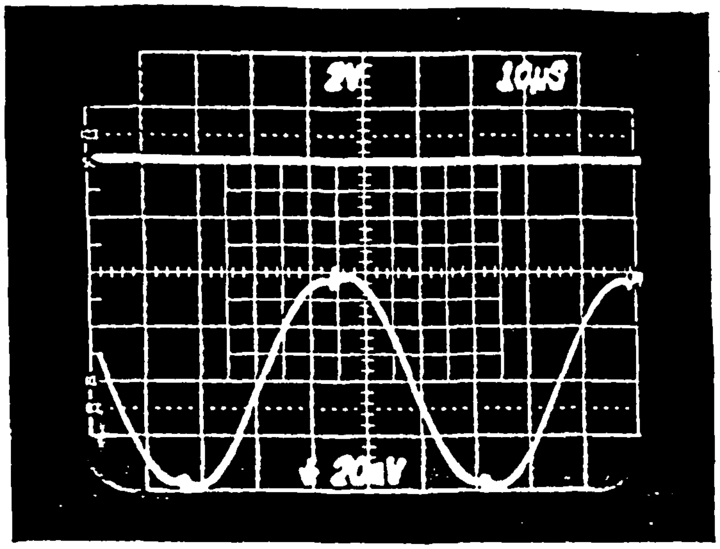


Figure 3.16: SPPM Cascaded Schwarz Converter Efficiencies Versus Load Current



Top - v_{02} 200 V/div
Bot - i_{02} 10 A/div
V_{s1} = 112 Vdc V_{02} = 0.0 Vdc
I_{S1} = 1.77 Adc I_{02} = 13.28 Adc

Figure 3.17: SPPM Cascaded Schwarz Converter Short Circuit Waveforms.

Table 6: SPPM Cascaded Schwarz Converter Percent Voltage Regulation Versus Load Current

% Load	V_{S1}	I_{S1}	V_{02}	I_{02}	V_{rms}	V_{rect}
100%	112	25.8	203	12.56	206	3.53
80%	112	20.7	204	10.04	206	3.53
75%	112	19.4	204	9.44	206	3.53
60%	112	15.5	204	7.52	206	3.53
50%	112	12.9	205	6.28	206	3.53
40%	112	10.5	205	5.04	206	3.53
35%	112	9.3	206	4.4	206	3.54
30%	112	8.0	206	3.76	203	3.54
25%	112	6.7	207	3.16	199	3.54
20%	112	5.4	207	2.52	197	3.54
15%	112	4.1	207	1.88	197	3.54
10%	112	2.8	208	1.24	199	3.54
0%	112	0.1	210	0	200	3.54
SC	112	1.77	175.9	1.0	0	13.28
OC	112	0.12	209.6	0.04	209	0

$$\%\ VR_{V_{02}} = \frac{210\text{-}203}{203} * 100 = 3.45\%$$

$$\%\ VR_{V_{rms}} = \frac{206\text{-}197}{206} * 100 = 4.37\%$$

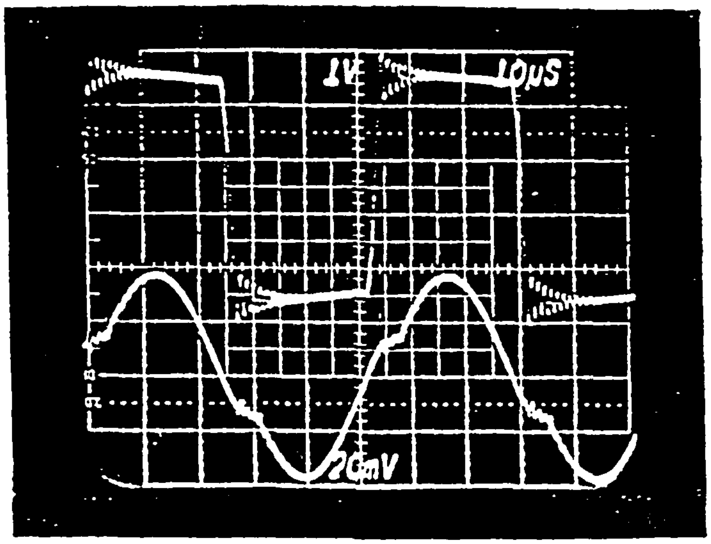
$$\%VR_{V_{rect}} = \frac{3.54 - 3.53}{3.53} * 100 = 0.28\%$$

All the previous data were taken for a system without a transmission cable. A section of transmission cable, which is described in reference [14], designed for high frequency applications was connected between the transformers of the second stage and the rectifier bridge shown in Figure 3.1. The specifications for this cable are given in Table 7. An explanation of the effects of the transmission cable on the cascaded Schwarz converter is given in reference [15]. Figure 3.18 and Figure 3.19 show the output voltage and current waveforms measured at the input and output of the cable respectively.

Table 7: Transmission Cable Specifications

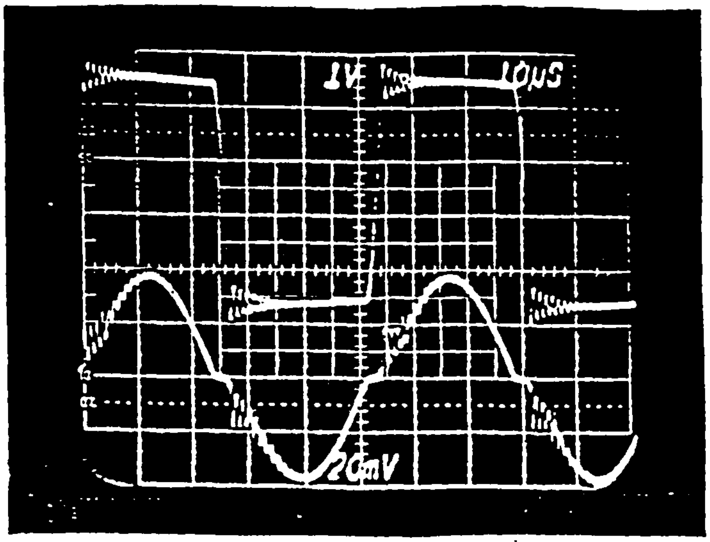
Voltage	Current	Frequency	Length
600 V_{rms}	60 A_{rms}	20 KHz	18.6 m

Inductance	Capacitance	Resistance
0.35 μH/m	0.0013 μF/m	0.83 mΩ/m
(Total - 6.51 μH)	Total - 0.024 μF)	Total - 15.4 mΩ)



Top - v_{cable} 100 V/div
Bot - i_{cable} 10 A/div
V_{S1} = 112 Vdc V_{02} = 202 Vdc
I_{S1} = 22 Adc I_{02} = 10.35 Adc

Figure 3.18: SPPM Cascaded Schwarz Converter Output Voltage and Current Measured at Input to the Transmission Cable



Top - v_{cable}	100 V/div
Bot - i_{cable}	10 A/div
V_{S1} = 112 Vdc	V_{02} = 202 Vdc
I_{S1} = 22 Adc	I_{02} = 10.35 Adc

Figure 3.19: SPPM Cascaded Schwarz Converter Output Voltage and Current Measured at Output of the Transmission Cable.

3.2 *Three Phase Cascaded Schwarz Converter.*

The series of tests which were performed on the single phase parallel module cascaded Schwarz converter were repeated on the three phase cascaded Schwarz converter. The output of the second stage for the three phase system was connected directly to a three phase rectified load. Figure 3.20 shows the locations for the various measured voltages and currents. These voltages and currents were measured in the same manner as those described for the single phase cascaded Schwarz converter.

Full load output voltage and current waveforms for each phase are shown in Figure 3.21 and Figure 3.22 respectively. Figure 3.23 shows the no-load voltage and current waveforms for phase A of the three phase cascaded Schwarz converter. The current supplied to the recycling rectifier by each phase under the no-load condition is presented in Figure 3.24. The three phase recycling rectifier circuit is shown in Figure B.9 of Appendix B. This circuit performs the same function as the recycling rectifier circuit described for the single phase parallel module cascaded Schwarz converter.

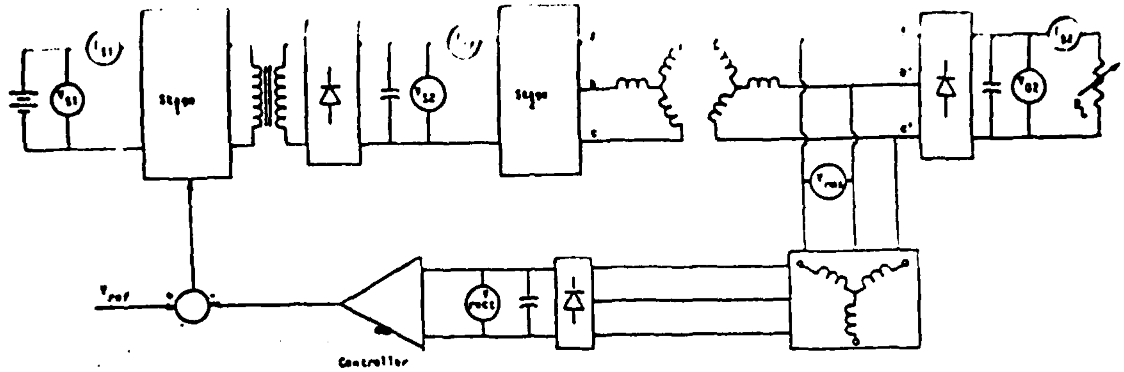
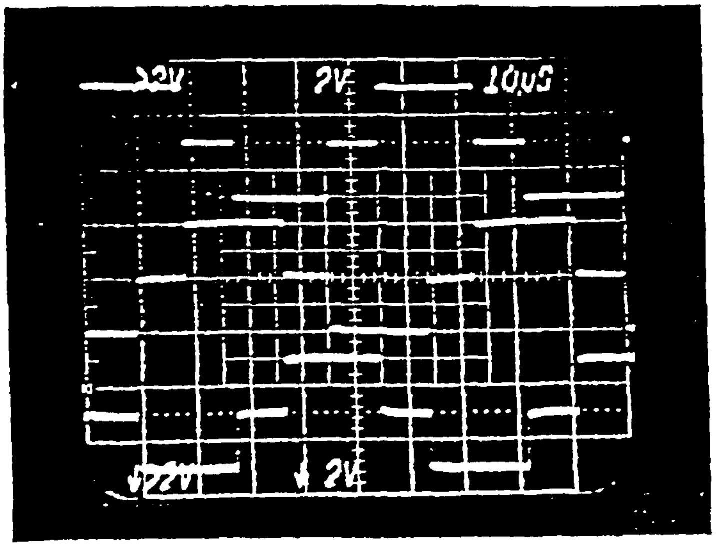
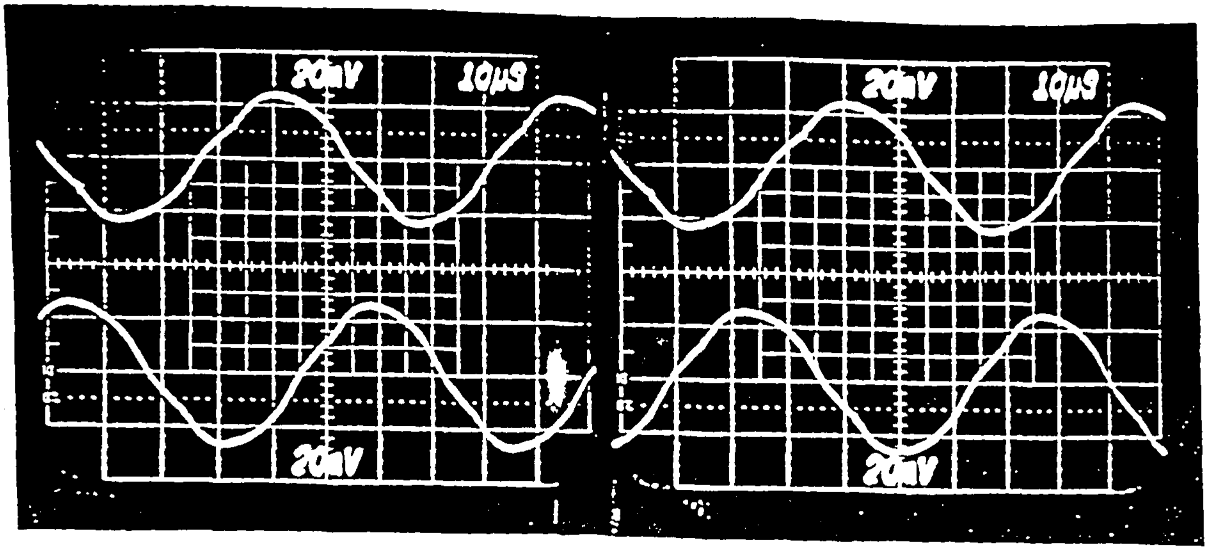


Figure 3.20: Test Locations for the Three Phase Cascaded Schwarz Converter.



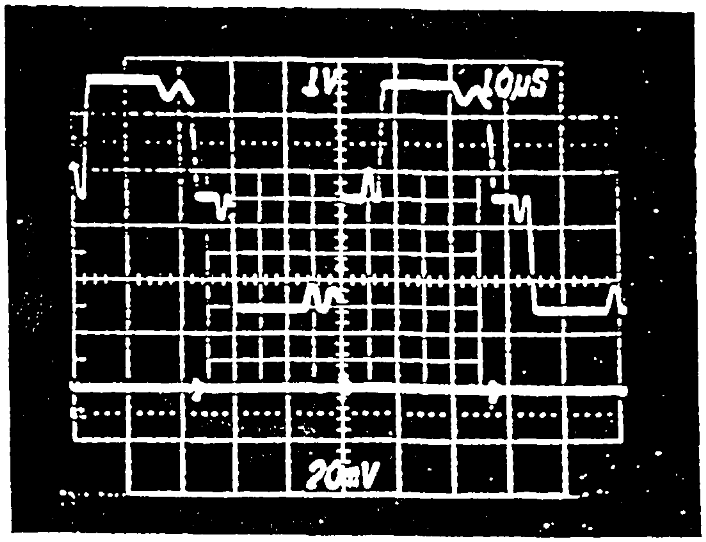
Top - v_{sb} 200 V/div
Mid - v_{bc} 200 V/div
Bot - v_{c1} 200 V/div
V_{S1} = 112 Vdc V_{02} = 202 Vdc
I_{S1} = 26 Adc I_{02} = 12 Adc

Figure 3.21: Full Load Voltage Waveforms for the Three Phase Cascaded Schwarz Converter.



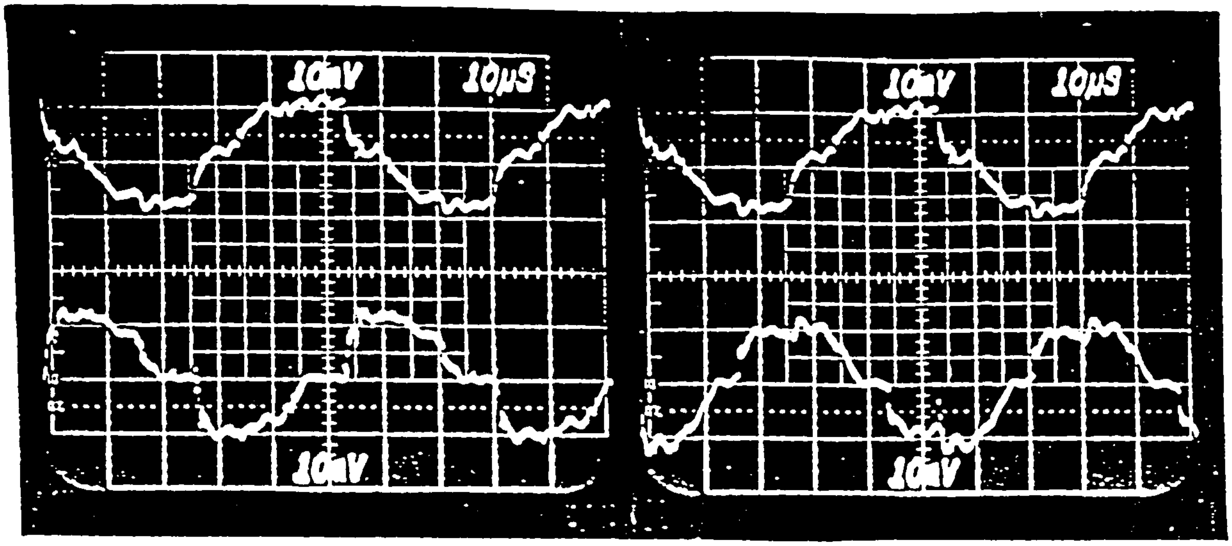
Top - i_a	10 A/div	Top - i_a	10 A/div
Bot - i_b	10 A/div	Bot - i_c	10 A/div
V_{S1} = 112 Vdc	V_{02} = 202 Vdc	V_{S1} = 112 Vdc	V_{02} = 202 Vdc
I_{S1} = 24.6 Adc	I_{02} = 12.2 Adc	I_{S1} = 24.6 Adc	I_{02} = 12.2 Adc

Figure 3.22: Full Load Current Waveforms for the Three Phase Cascaded Schwarz Converter



Top - V_{an}	100 V/div
Bot - i_a	10 A/div
V_{S1} = 112 Vdc	V_{02} = 208 Vdc
I_{S1} = 0.15 Adc	I_{02} = 0.0 Adc

Figure 3.23: No Load Voltage and Current Waveforms for Phase A of the Three Phase Cascaded Schwarz Converter

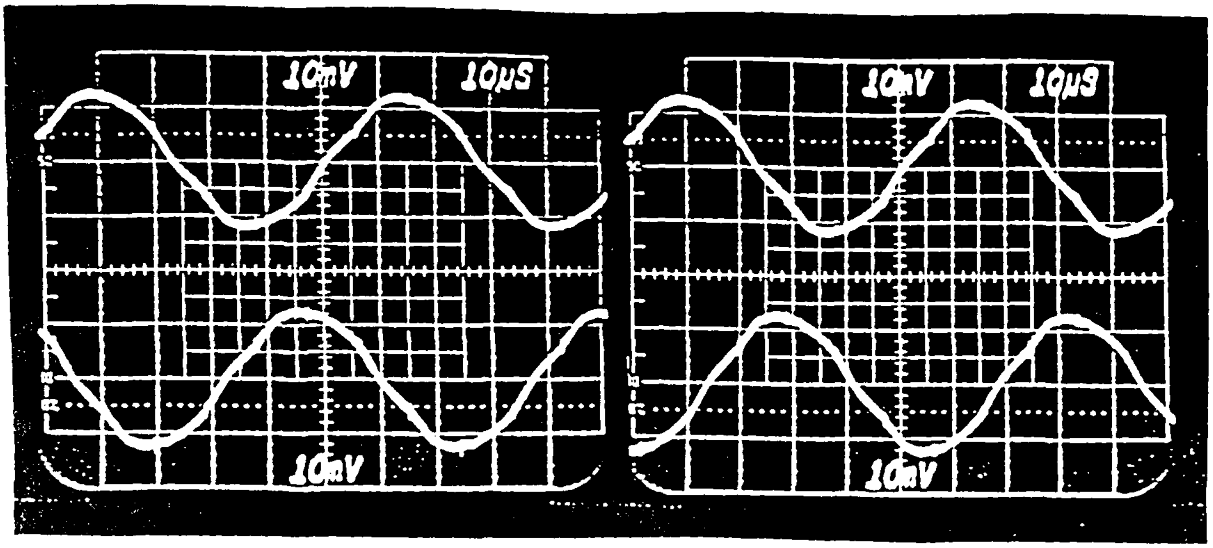


Top - $i_{a\text{ - recycle}}$	0.2 A/div	Top - $i_{a\text{ - recycle}}$	0.2 A/div
Bot - $i_{b\text{ - recycle}}$	0.2 A/div	Bot - $i_{c\text{ - recycle}}$	0.2 A/div
V_{S1} = 112 Vdc	V_{02} = 207 Vdc	V_{S1} = 112 Vdc	V_{02} = 207 Vdc
I_{S1} = 0.15 Adc	I_{02} = 0.0 Adc	I_{S1} = 0.15 Adc	I_{02} = 0.0 Adc

Figure 3.24: Recycling Rectifier Current Waveform for the Three Phase Cascaded Schwarz Converter.

The load sharing between the individual inverters of the second stage is presented in Figure 3.25. Figure 3.25 shows the current in the resonant inductor of each inverter at full load. As shown, the currents are very well matched for the inverters of the second stage. Also, a comparison of Figure 3.7 and Figure 3.25, shows that the power levels of the three phase and the single phase parallel module systems are almost equal, as was assumed earlier. Therefore, the design algorithm for the single phase parallel module cascaded Schwarz converter can be used in the design of the three phase cascaded Schwarz converter.

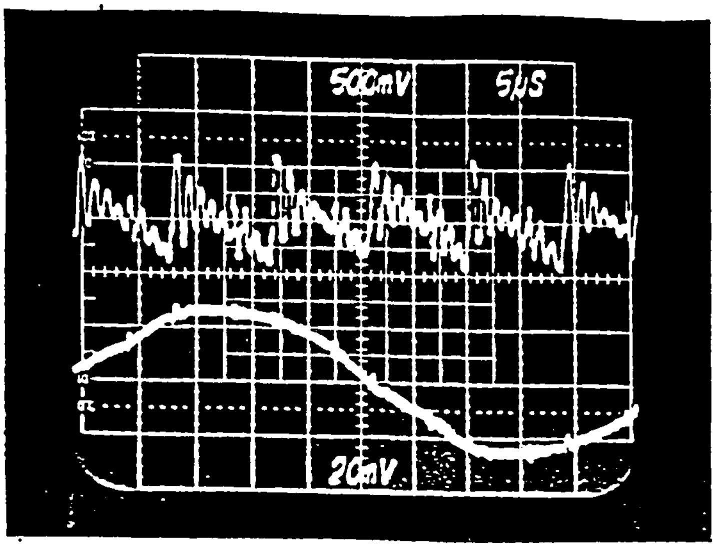
The effects of the size of the output filter capacitor are shown in Figure 3.26 through Figure 3.30. These figures show that the dominant voltage ripple frequency is six times larger than the operating frequency of the second stage. Also from Figure 3.26, the full load output voltage of 202 Vdc is maintained without an output filter capacitor. Table 8 summarizes the information given in these figures. This information will be used later in the filter comparison between the single phase and three phase systems.



Top - $i_{a_{10}}$	5 A/div	Top - $i_{a_{10}}$	5 A/div
Bot - $i_{b_{10}}$	5 A/div	Bot - $i_{c_{10}}$	5 A/div
V_{S1} = 112 Vdc	V_{02} = 202 Vdc	V_{S1} = 112 Vdc	V_{02} = 202 Vdc
I_{S1} = 25 Adc	I_{02} = 11.58 Adc	I_{S1} = 25 Adc	I_{02} = 11.58 Adc

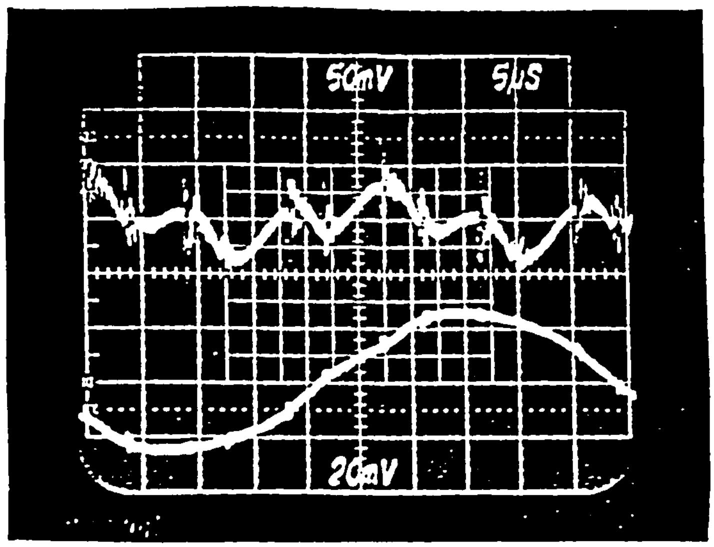
Figure 3.25: Three Phase Cascaded Schwarz Converter Current Sharing Waveforms.

The amount of current ripple flowing in the input and output filter capacitors is shown in Figure 3.31 through Figure 3.33. Figure 3.31 shows the rectified output current of stage 2 and the ripple current flowing in the output filter capacitor. As shown in this figure, all of the ripple current is flowing into the filter capacitor. Figure 3.32 shows the rectified output current of stage 1 and the ripple current into the filter capacitor between stages 1 and 2. Figure 3.33 shows the input current of stage 2 and the ripple current into the filter capacitor between stages 1 and 2. The filter capacitor between stages 1 and 2 acts as an output filter for stage 1 and the input filter for stage 2. Therefore, this capacitor must be sized to handle the ripple currents from both stages.



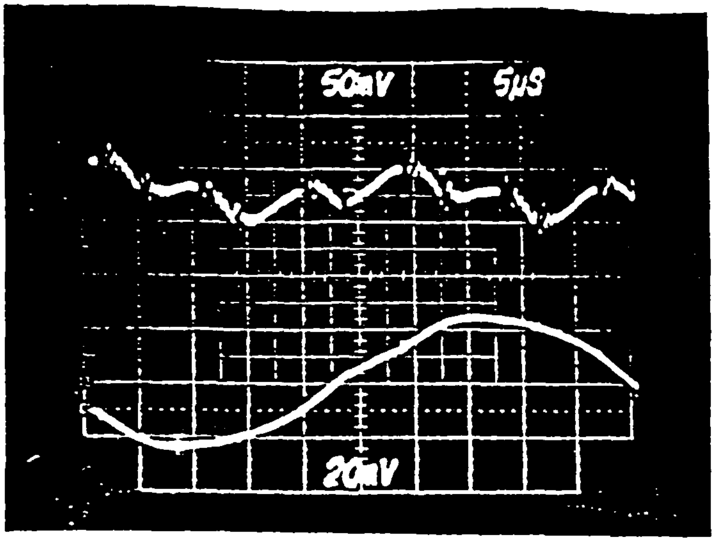
Top - V_{02} (ripple)	50 V/div
Bot - i_a	10 A/div
V_{S1} = 112 Vdc	V_{02} = 202 Vdc
I_{S1} = 26 Adc	I_{02} = 12 Adc

Figure 3.26: Three Phase Cascaded Schwarz Converter without an Output Filter Capacitor.



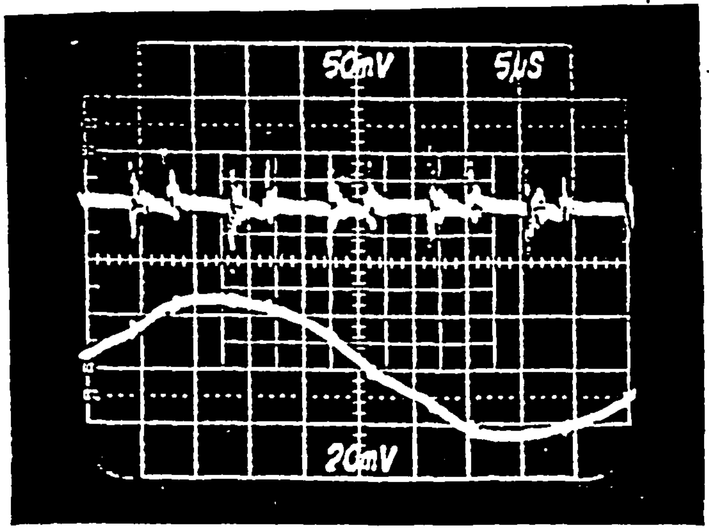
Top - V_{02} (ripple)	5 V/div
Bot - i_a	10 A/div
V_{S1} = 112 Vdc	V_{02} = 202 Vdc
I_{S1} = 26 Adc	I_{02} = 12 Adc

Figure 3.27: Three Phase Cascaded Schwarz Converter with a 0.5-μF Output Filter Capacitor.



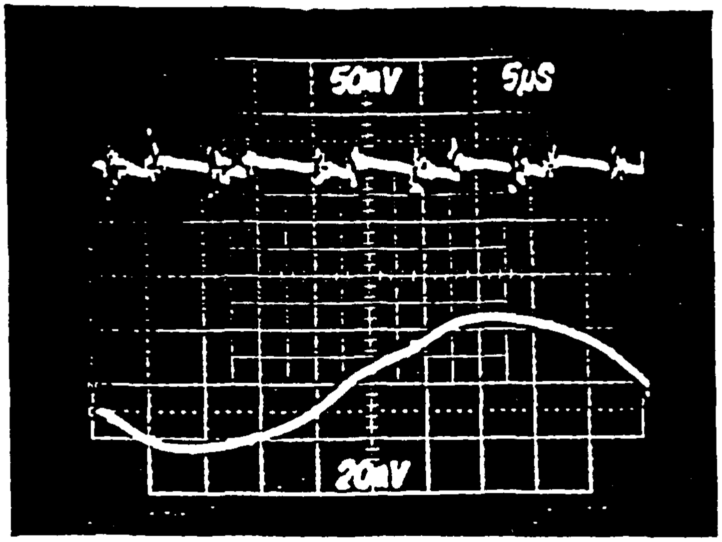
Top - V_{02} (ripple)	5 V/div
Bot - i_a	10 A/div
V_{S1} = 112 Vdc	V_{02} = 202 Vdc
I_{S1} = 26 Adc	I_{02} = 12 Adc

Figure 3.28: Three Phase Cascaded Schwarz Converter with a 0.7-μF Output Filter Capacitor.



Top - V_{02} (ripple)	5 V/div
Bot - i_a	10 A/div
V_{S1} = 112 Vdc	V_{02} = 202 Vdc
I_{S1} = 26 Adc	I_{02} = 12 Adc

Figure 3.29: Three Phase Cascaded Schwarz Converter with a 5.0-μF Output Filter Capacitor.

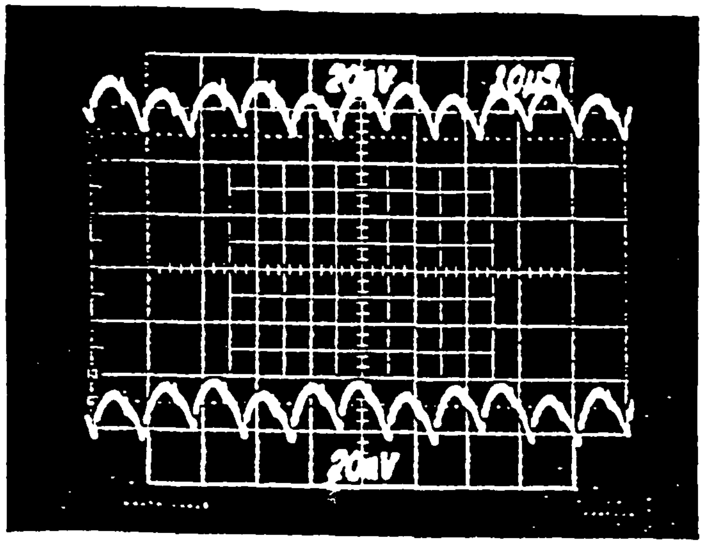


Top - V_{02} (ripple) 5 V/div
Bot - i_a 10 A/div
V_{S1} = 112 Vdc V_{02} = 202 Vdc
I_{S1} = 26 Adc I_{02} = 12 Adc

Figure 3.30: **Three Phase Cascaded Schwarz Converter with a 100-µF Output Filter Capacitor**

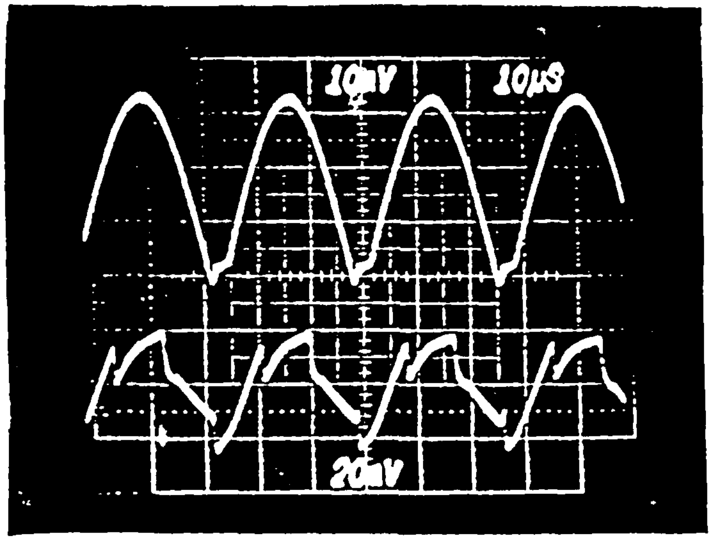
Table 8: **Three Phase Cascaded Schwarz Converter Output Filter Results**

Capacitor (µF)	$V_{02\text{-ripple}}$ (V_{p-p})	V_{02} (Vdc)	I_{02} (Adc)	V_{S1} (Vdc)	I_{S1} (Adc)
0.0	100	202	12	112	26
0.5	6.5	202	12	112	26
0.7	5.0	202	12.08	112	24.48
5.0	**	202	12.08	112	24.48
100	**	202	12.08	112	24.54



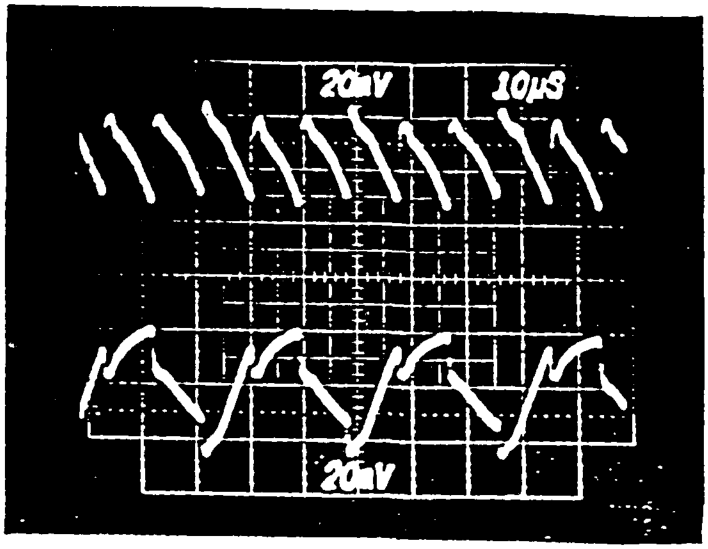
Top - i_{02}	2 A/div
Bot - $i_{c\text{-ripple}}$	2 A/div
V_{S1} = 112 Vdc	V_{02} = 202 Vdc
I_{S1} = 24.3 Adc	I_{02} = 12.0 Adc

Figure 3.31: **Output Current Ripple from Stage 2 of the Three Phase Cascaded Schwarz Converter with a 5.0-µF Filter Capacitor.**



Top - i_{01}	5 A/div
Bot - $i_{c\text{-}12}$	10 A/div
V_{S1} = 112 Vdc	V_{02} = 202 Vdc
I_{S1} = 24.3 Adc	I_{02} = 12.12 Adc

Figure 3.32: **Rectified Output Current of Stage 1 and the Capacitor Ripple Current between Stages 1 and 2 of the Three Phase Cascaded Schwarz Converter with a 270-µF Filter Capacitor.**



Top - i_{S2}	4 A/div
Bot - i_{c12}	10 A/div
V_{S1} = 112 Vdc	V_{02} = 202 Vdc
I_{S1} = 24.3 Adc	I_{02} = 12.12 Adc

Figure 3.33: Input Current of Stage 2 and the Capacitor Ripple Current between Stages 1 and 2 of the Three Phase Cascaded Schwarz Converter with a 270-µF Filter Capacitor.

Efficiency, short circuit and open circuit data are shown in Table 9. The average total efficiency for the given load range is 87.59%. The average stage 1 and stage 2 efficiencies over the given load range are 93.44% and 93.44%, respectively. As exhibited by the data,the efficiencies change by only a few percent over the given load range. Note these efficiencies do not include the losses of the control circuits, but these losses are quite small because of the high input impedance of the transistor switching devices. Figure 3.34 shows graphically how the efficiency of each stage and the overall system efficiency varies under conditions ranging from full load to ten percent of full load. Table 9 shows that the output current I_{02} is limited to 13.48 Adc at short circuit because of the current limiting circuit. Also an inherent current limiting characteristic exists associated with the use of the γ controller, as explained previously. Figure 3.35 shows the short circuit output current waveforms for each phase of this system.

Table 9: **Three Phase Cascaded Schwarz Converter Efficiency, Short Circuit and Open Circuit Data**

% Load	V_{S1}	I_{S1}	V_{S2}	I_{S2}	V_{O2}	I_{O2}
100%	112	25.02	267.2	10.08	202	12.36
90%	112	22.56	256.6	9.44	202	11.12
80%	112	20.07	246.8	8.68	202	9.88
70%	112	17.52	237.6	7.88	202	8.64
60%	112	15.0	229.4	6.96	203	7.40
50%	112	12.63	222.6	6.0	203	6.20
40%	112	10.23	216.9	4.92	203	4.96
30%	112	7.83	212.7	3.8	204	3.72
20%	112	5.25	210.4	2.56	204	2.48
10%	112	2.79	209.0	1.32	205	1.24
SC	112	2.01	180.9	1.12	0	13.48
OC	112	0.15	207.3	0.08	207	0

P_{IN1}	n_1	$P_{OUT1} = P_{IN2}$	n_2	P_{OUT2}	n_{TOT}
2802.24	96.12	2693.38	92.70	2496.72	89.10
2526.72	95.87	2422.30	92.73	2246.24	88.90
2247.84	95.30	2142.22	93.16	1995.76	88.78
1962.24	95.42	1872.29	93.22	1745.28	88.95
1680.00	95.04	1596.62	94.09	1502.20	89.42
1414.56	94.42	1335.60	94.23	1258.60	88.97
1145.76	93.14	1067.15	94.35	1006.88	87.88
876.96	92.17	808.26	93.89	758.88	86.54
588.00	91.60	538.62	93.92	505.92	86.03
312.48	88.29	275.88	92.14	254.20	81.35

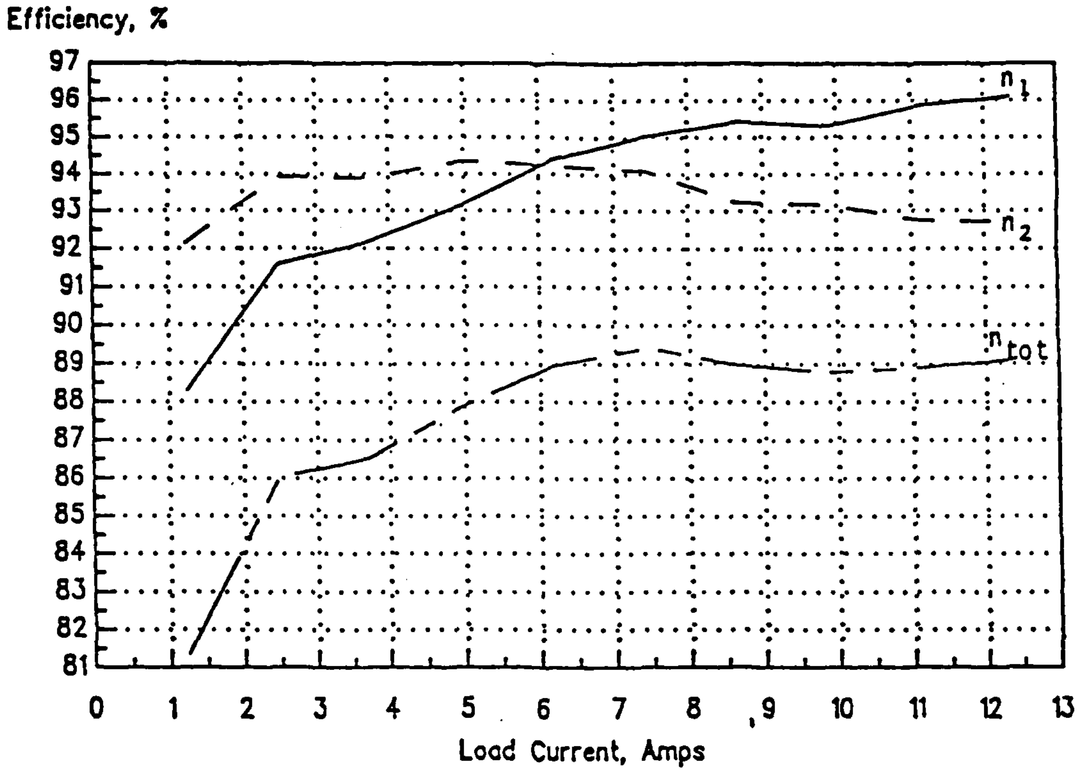
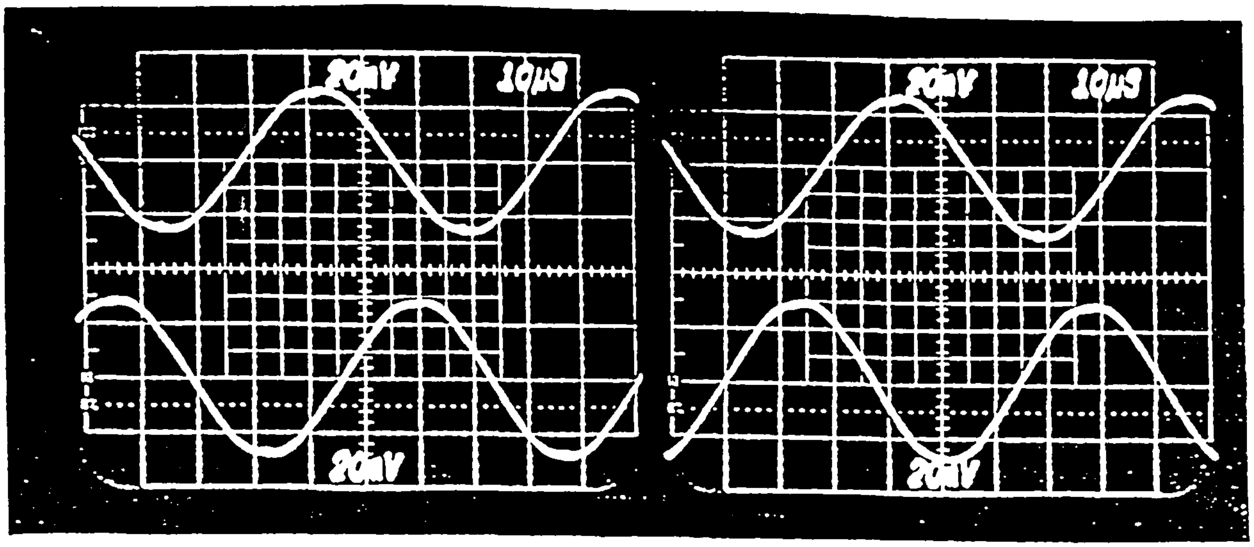


Figure 3.34: Three Phase Cascaded Schwarz Converter Efficiencies Versus Load Current

Table 9 shows that the output current I_{02} is limited to 13.48 Adc at short circuit because of the current limiting circuit. Also an inherent current limiting characteristic exists associated with the use of the γ controller, as explained previously. Figure 3.35 shows the short circuit output current waveforms for each plane of this system.



Top - i_a	10 A/div	Top - i_a	10 A/div
Bot - i_b	10 A/div	Bot - i_c	10 A/div
V_{S1} = 112 Vdc	V_{02} = 0.0 Vdc	V_{S1} = 112 Vdc	V_{02} = 0.0 Vdc
I_{S1} = 2.01 Adc	I_{02} = 13.48 Adc	I_{S1} = 2.01 Adc	I_{02} = 13.48 Adc

Figure 3.35: Three Phase Cascaded Schwarz Converter Short Circuit Waveforms.

Percent voltage regulation versus load current data are given in Table 10. The three different voltages measured for this test were the output voltage, V_{02}, the line to line rms voltage, $V_{rms\text{-}ab}$, across the phase A and B sensing transformer primaries (PTA and PTB of Figure B.15 in Appendix B) and the rectified output voltage, $V_{rect\text{-}abc}$, from the sensing transformer secondaries. The voltages V_{02} and $V_{rms\text{-}ab}$ are only regulated indirectly, whereas $V_{rect\text{-}abc}$ is directly regulated. The percent voltage regulation for the output line, using $V_{rect\text{-}abc}$ as the control voltage, is 0.29% from full load to no-load. The percent voltage regulation using V_{02} and $V_{rms\text{-}ab}$ is 2.48% and 6.55%, respectively.

Table 10: **Three Phase Cascaded Schwarz Converter Percent Voltage Regulation Versus Load Current**

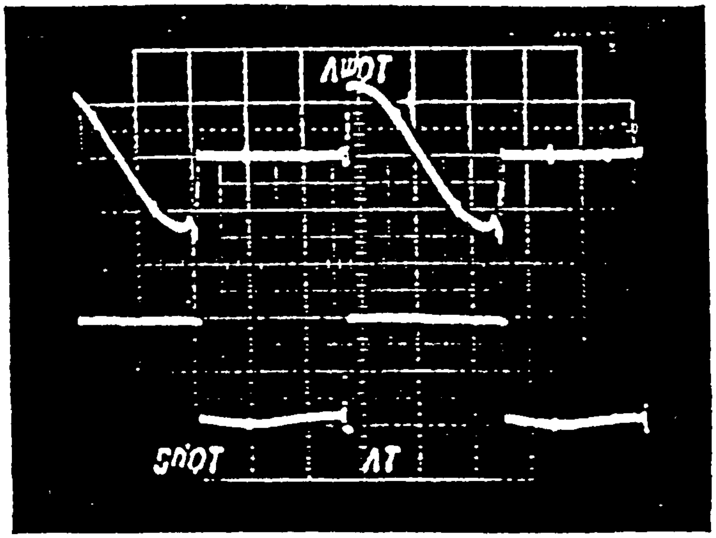
% Load	V_{S1}	I_{S1}	V_{02}	I_{02}	$V_{rms\text{-}ab}$	$V_{rect\text{-}abc}$
100%	112	25.02	202	12.36	168	3.5
80%	112	20.07	202	9.88	168	3.49
75%	112	18.84	202	9.28	168	3.49
60%	112	15.0	203	7.40	168	3.49
50%	112	12.63	203	6.20	168	3.49
40%	112	10.23	203	4.96	167	3.49
35%	112	9.06	203	4.32	167	3.49
30%	112	7.83	204	3.72	167	3.49
25%	112	6.45	204	3.08	166	3.49
20%	112	5.25	205	2.48	166	3.49
15%	112	3.96	205	1.84	166	3.5
10%	112	2.79	205	1.24	163	3.5
0%	112	0.15	207	0	157	3.5

$$\%VR_{V_{02}} = \frac{207 - 202}{202} * 100 = 2.48\%$$

$$\%VR_{V_{rms\text{-}ab}} = \frac{168 - 157}{168} * 100 = 6.55\%$$

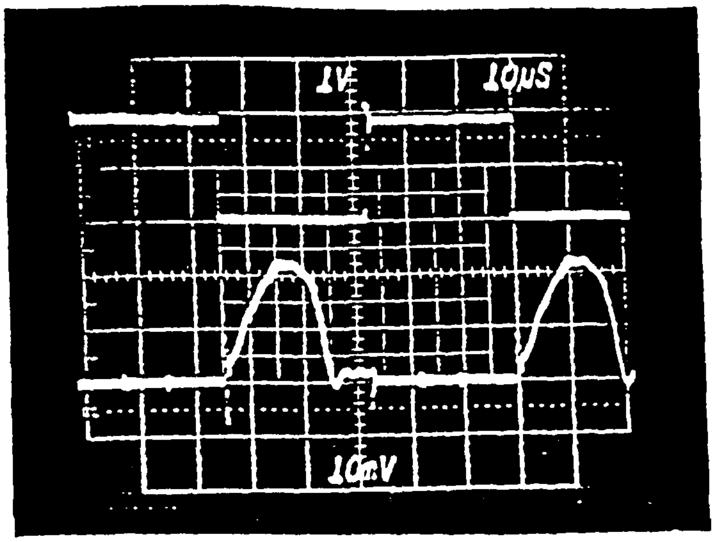
$$\%VR_{V_{rect\text{-}abc}} = \frac{3.5 - 3.49}{3.5} * 100 = 0.29\%$$

Two unbalanced fault conditions that can arise when operating a three phase four wire transmission system are a single phase to neutral fault and a line-to-line fault. These faults result in an unbalanced operating condition in the three inverters of the second stage. Figure 3.36 through Figure 3.38 show the effects of a single line to neutral fault. This fault was placed across the secondary of the phase A isolation transformer. As seen in Figure 3.36 through Figure 3.38, the currents in the three inverters are not balanced. Also, as shown in Figure 3.38 the switching transistors of phase C are being force commutated. Voltage snubber circuits are provided for these transistors, but they are normally only needed to snub the voltage transient that occurs because of the reverse recovery current that flows through the anti-parallel diodes when they turn off. If these snubbers were designed for a forced commutated fault current, they would be much larger, which is undesirable. The single line to neutral fault can only occur if the neutral



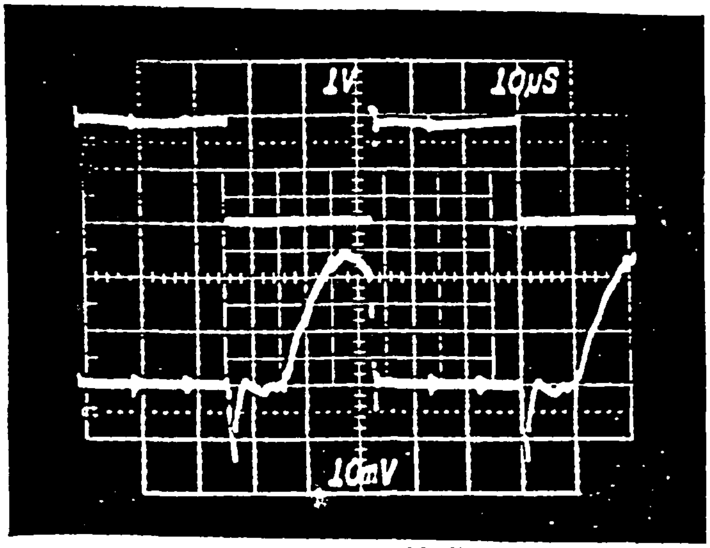
Top - $V_{ce\text{-}Q3}$ 100 V/div
Bot - $i_{Q3} + i_{D3}$ 5 A/div
V_{S1} = 112 Vdc V_{02} = 165 Vdc
I_{S1} = 2.5 Adc I_{02} = 1.05 Adc

Figure 3.36: Phase A Transistor Voltage and Current During a Single Line to Ground Fault on Phase A.



Top - $V_{ce\text{-}Q3}$ 100 V/div
Bot - $i_{Q3} + i_{D3}$ 5 A/div
V_{S1} = 112 Vdc V_{02} = 165 Vdc
I_{S1} = 2.5 Adc I_{02} = 1.05 Adc

Figure 3.37: Phase B Transistor Voltage and Current During a Single Line to Ground Fault on Phase A.

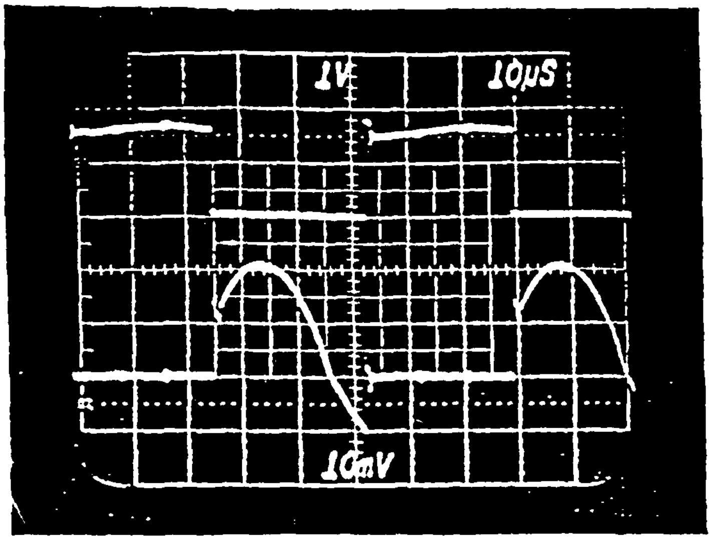


Top - $V_{ce\text{-}Q3}$	100 V/div
Bot - $i_{Q3} + i_{D3}$	5 A/div
V_{S1} = 112 Vdc	V_{02} = 165 Vdc
I_{S1} = 2.5 Adc	I_{02} = 1.05 Adc

Figure 3.38: Phase C Transistor Voltage and Current During a Single Line to Ground Fault on Phase A.

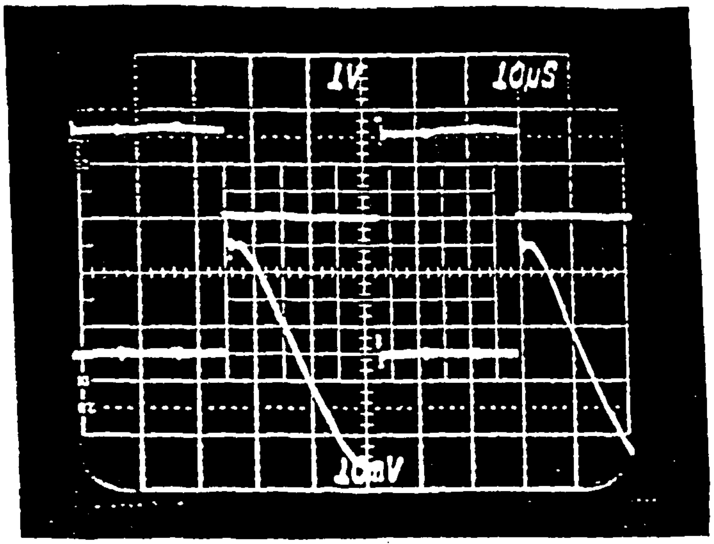
line is part of the transmission system, or if the fault occurs internal to the isolation transformer. The three phase cascaded Schwarz converter used in this present research does not make the neutral wire available in the transmission system (see Figure 1.2). Therefore, only an internal fault in the isolation transformer can produce a single line to neutral fault. The likelihood of this condition occurring can be greatly reduced by proper transformer design.

The line-to-line fault is shown in Figure 3.39 through Figure 3.41. This fault was produced by placing a short across the phase B and C transmission lines. As shown in these figures, this fault also causes unbalanced currents to flow in the three inverters. However, this fault condition does not cause a forced commutation condition to occur.



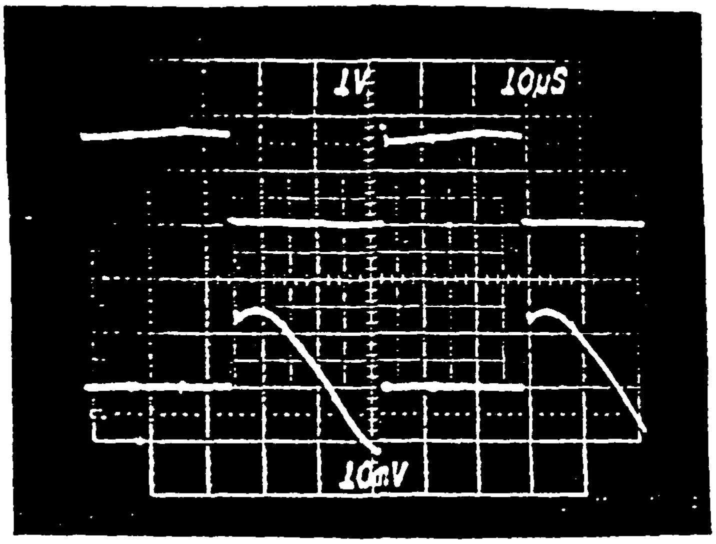
Top - $V_{ce\text{-}Q3}$	100 V/div
Bot - $i_{Q3} + i_{D3}$	5 A/div
V_{S1} = 112 Vdc	V_{02} = 86 Vdc
I_{S1} = 5.5 Adc	I_{02} = 5.04 Adc

Figure 3:39: Phase A Transistor Voltage and Current During a Line-to-Line Fault between Phases B and C.



Top - $V_{ce\text{-}Q3}$	100 V/div
Bot - $i_{Q3} + i_{D3}$	5 A/div
V_{S1} = 112 Vdc	V_{02} = 86 Vdc
I_{S1} = 5.5 Adc	I_{02} = 5.04 Adc

Figure 3.40: Phase B Transistor Voltage and Current During a Line-to-Line Fault between Phases B and C.



Top - $V_{ce\text{-}Q3}$ 100 V/div
Bot - $i_{Q3} + i_{D3}$ 5 A/div
$V_{S1} = 112$ Vdc $V_{02} = 86$ Vdc
$I_{S1} = 5.5$ Adc $I_{02} = 5.04$ Adc

Figure 3.41: Phase C Transistor Voltage and Current During a Line-to-Line Fault between Phases B and C.

The three phase transmission system is capable of supplying two phase rectified loads and three phase rectified loads. Introducing a two phase rectified load onto the transmission system (see Figure 1.2) does cause the system to become unbalanced. Table 11 shows the results of operating the three phase cascaded Schwarz converter with a three phase rectified load and a two phase rectified load. For this test, a two phase load was connected across phase A and phase B of the transmission system The results of Table 11 indicate that for a given two phase rectified load, there must be a minimum three phase recitified load to maintain output voltage to the two phase load. This implies that if two phase loads are used, they should be relatively small, and that they should be more or less equally distributed on all three phases.

Another condition shown in the results of Table 11 is the current shared by the individual inverters of the second stage may also contribute to the two phase output voltage regulation problem. The data given indicate that the peak-to-peak output current from phase C must be greater than that of phase A to provide a constant output voltage at the two phase rectified load. Note that the voltage regulation of the three phase rectified load is not affected by the two phase rectified load, as shown in Tables 10 and 11 by comparing the output voltage, V_{O2}.

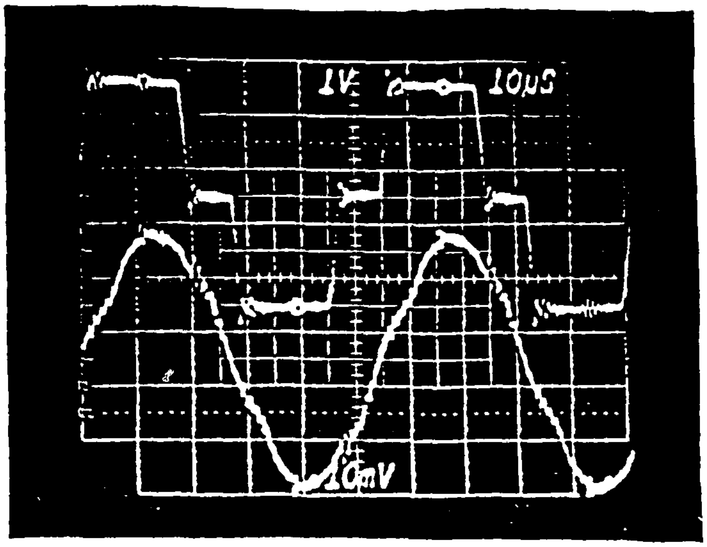
Although the component count is less, there is some question as to whether there is any real advantage to using two phase loads. By using three phase rectified loads, the number of rectifier diodes increases by two, but the size of the output filter capacitor can be reduced. This trade-off and the fact that a two phase rectified load introduces voltage regulation problems and unbalanced phase currents suggests that using a two phase rectifier has no real advantage over usign three phase rectifiers exclusively.

All the previous data were taken for a system without a transmission cable. The section of transmission cable described previously was connected between the transformers of the second stage and the rectifier bridge shown in Figure 3.20. Figure 3.42 and Figure 3.43 show the output voltage and current waveforms measured at the input and output of the cable respectively.

Table 11: Three Phase Cascaded Schwarz Converter Operated with a Two Phase Rectified Load.

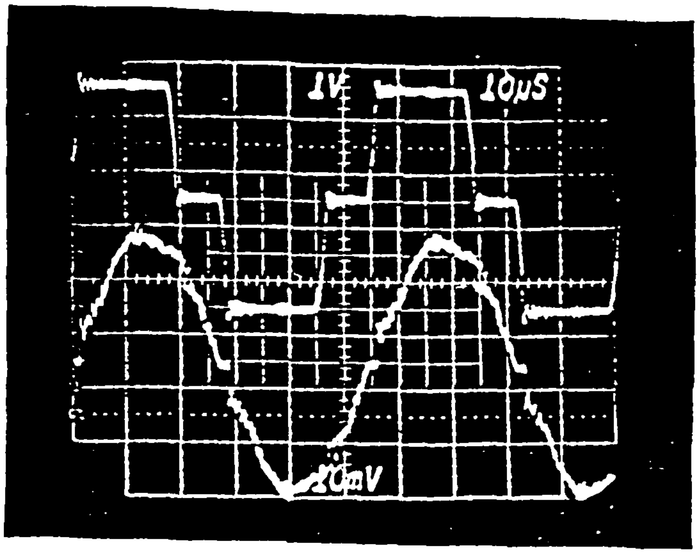
I_{S1}	V_{O2}	I_{O2}	V_{SPR}	I_{SPR}	$V_{l-l\ rms}$	$i_{a\ peak}$	$i_{b\ peak}$	$i_{c\ peak}$
4.17	207	1	191.3	1	160	5.0	5.0	2.8
6.36	205	2	204.4	1	166	6.4	6.0	5.0
8.46	204	3	204.5	1	165	7.8	8.8	8.0
10.41	204	4	204.4	1	165	9.8	11.0	10.0
12.33	203	5	204.5	1	165	11.6	13.0	12.2
14.28	203	6	204.3	1	165	13.4	15.0	14.4
16.32	203	7	204.2	1	165	15.5	17.5	16.5
18.36	202	8	204.5	1	165	17.5	19.5	19
20.34	202	9	204.3	1	165	19.5	21.5	21.0
22.38	202	10	204.1	1	165	21.5	24.0	23.5
24.42	202	11	204.0	1	165	23.5	26.5	25.5
5.91	207	1	173.1	2	153	9.6	9.0	3.2
7.95	206	2	173.5	2	153	9.8	10.6	6.0
10.08	205	3	179.5	2	155	10.4	12.0	9.0
12.27	204	4	202.6	2	165	11.4	13.0	12.0
14.28	203	5	203	2	165	13.2	15.0	14.2
16.29	203	6	203.2	2	165	15.0	17.5	17.0
18.3	203	7	203.5	2	166	17.5	19.5	18.5
20.37	202	8	203.4	2	166	19.5	21.5	21.0
22.35	202	9	203.2	2	166	21.5	24.0	23.0
24.36	202	10	203.2	2	166	23.5	26.0	25.5
7.17	207	1	154	3	140	13.5	13.5	3.4
9.12	206	2	154.3	3	140	13.5	14.5	7.0
11.04	206	3	155.0	3	140	13.5	16.5	10.0
13.29	205	4	165.8	3	145	14.0	17.5	13.0
15.69	204	5	180.4	3	153	16.0	19.0	15.5
18.24	203	6	200.4	3	164	17.0	19.5	18.5
20.37	203	7	202.0	3	165	19.0	22.0	21.0
22.38	202	8	202.2	3	165	21.5	24.0	23.0
24.39	202	9	202.2	3	165	23.5	26.5	25.5
8.07	207	1	134.5	4	125	16.0	16.5	3.4
9.96	206	2	134.6	4	125	16.0	18.5	6.6
11.85	206	3	134.9	4	125	16.0	20.0	10.5
14.01	205	4	140.1	4	127	17.5	22.0	13.0
16.32	204	5	147	4	130	18.0	23.5	16.0
18.81	204	6	157.9	4	136	19.5	25.5	18.5
21.48	203	7	175.0	4	147	21.5	26.5	21.5
24.18	203	8	195.2	4	161	23.0	27.0	25.0

SPR = Single Phase Rectifier



Top - V_{ab}	100 V/div
Bot - i_a	5 A/div
V_{S1} = 112 Vdc	V_{02} = 202 Vdc
I_{S1} = 23 Adc	I_{02} = 10.77 Adc

Figure 3.42: **Three Phase Cascaded Schwarz Converter Output Voltage and Current Measured at Input to the Transmission Cable.**



Top - V_{ab}	100 V/div
Bot - i_a	5 A/div
V_{S1} = 112 Vdc	V_{02} = 202 Vdc
I_{S1} = 23 Adc	I_{02} = 10.77 Adc

Figure 3.43: **Three Phase Cascaded Schwarz Converter Output Voltage and Current Measured at Output of the Transmission Cable.**

Section IV

CONCLUSION FOR PART I

4.1 Filter Comparison

As indicated in Tables 4 and 8, the size of the output filter capacitors can be reduced by two orders of magnitude by use of three phase system instead of a single phase system. The single phase system with a 100-μF output filter capacitor provices a 5.0-V peak-to-peak voltge ripple. The same voltage ripple on the three phase system can be obtained by using a 0.,7-μF output filter capacitor. For the three phase system, the lowest order voltage ripple frequency is six times larger than the operating frequency. In the single phase system, the lowest order voltage ripple frequency is only two times larger than the operating frequency. The full load average output voltage of 202 Vdc can be maintained on the three phase system without an output filter capacitor, but it requires a 5.0-μF output filter capacitor for the single phase system. The ripple current for the single phase system is 11.51 times larger than that of the three phase system. Therefore, there is less heat generated by the I^2R (where R is the equivalent series resistance of the capacitor) losses associated with the three phase filter capacitors and the current ripple rating for the three phase capacitors will be smaller. Thus the three phase system does provide some advantages over the single phase system through the reduction of the filter requirements.

4.2 Fault Tolerance

The three ph~~ system has two possible short circuit conditions on its output line if a three conductor transmission line is used. They are a line-to-line fault and a short across all three lines of the transmission system. Each of these faults were studied and we found that the system can operate continuously under either condition with no damaging effects on the converter. The single phase system can also operate continuously into a dead short on its output line with no damaging effects. For each system, the short circuit currents during the fault condition are limited initially by the inherent current limiting characteristic and by the current limiting circuit in the steady state.

Another fault condition, which can occur only if a ground wire is used in the three phase transmission system or if there is a fult internal to the isolation transformer, is a single line to neutral fault. This fault causes a forced commutation condition to arise in one of the inverter phases.

Both systems are capable of operating into an open circuit. Under this condition, the recycling rectifier is used to help keep the no-load output voltage very close to the full load output voltage. This circuit, as stated previously, also prevents the output filter capacitors from charging to a transient voltage peak during the open circuited condition.

4.3 Transmission Line Comparison

As stated in subsection 2.5, the transmission line copper weight is independent of the number of phases (for $n \geq 2$) as lone as the line-to-neutral voltages are constant, there is no neutral wire and the losses are constant for a given volt-ampere rating. Also, the single phase system will have the same copper weight as a multiphase system if the transmission line has one rail above neutral and the other rail below. It has been stated that the neutral wire should not be used for the three phase system because of the unfavorable conditions caused by a single line to neutral fault. Therefore, given that the volt-ampere ratings and the line-to-neutral voltages are equal for the single phase and the three phase systems, the three wire transmission line of the three phase cascaded Schwarz converter will have the same copper weight as the two wire transmission line used for the single phase parallel module cascaded Schwarz converter.

4.4 Summary

The total efficiencies of the three phase system and the single phase system were almost identical. The three phase system was 89.10% efficient and the single phase system was 88.24% efficient The full load output power of the three phase and single phase systems were 2497 watts and 2550 watts, respectively, for a percent difference of 2.1%. Also, as stated in subsection 4.3 the transmission line copper weight for the two transmission systems are equal. Therefore, neither system has a significant cable weight advantage over the other. The three phase system does gain an advantage because of the reduction in size of the filter capacitors. The three phase system has an output filter capacitor that is roughly two orders of magnitude smaller in size when compared to the single phase output filter capacitor.

Both systems can be designed using the design algorithm for the single phase parallel module cascaded Schwarz converter. This program provides certain steady-state calculations such as the current and voltage ratings for the switching devices, antiparallel diodes, and resonant components. The program also calculates the size of the resonant capacitors and inductors required and the amount of turn-off time available for the switching devices.

PART II: ISOLATION OF FAULTED MODULES IN SERIES RESONANT CONVERTERS

Section V

INTRODUCTION FOR PART II

Previous work on series resonant (Schwarz) converters has established the feasibility of various items, such as the following:

1. dc distribution systems driven by these converters.
2. Single phase and three phase constant frequency systems driven by cascade versions of these converters.
3. The operation of several converters in parallel for either AC or dc distribution systems.

Because of its advantages, there is a strong incentive to build larger Schwarz converters by using several modules in series and/or parallel combinations. The research described here is concerned with a preliminary study of a basic problem with modular systems, namely how to detect and isolate a faulted module.

It is anticipated that future electric distribution systems for airplanes and/or spacecraft will exceed the 100kW level, and some may operate at levels of several megawatts. Because of these high power levels, the electronic power converters must either use series-parallel combinations of switching devices or use combinations of individual modules. Of these two possibilities, modular design is usually preferred since it allows the removal of a bad module in case of a component failure. This is especially important for future systems that must be autonomous and must operate for long periods of time without manual servicing.

It is still unknown if these future distribution systems will be ac or dc. Both types are currently under study by various research groups, and each has its own set of advantages and disadvantages. Regardless of which type of system is ultimately chosen for a given application, it is quite likely that Schwarz converters will be utilized because of their high efficiency, low component stress, and fault tolerant operation. In dc systems, single stage versions of the Schwarz provide a convenient circuit for both voltage conversion and regulation. In ac systems, it has been demonstrated that a cascaded version of the Schwarz can provide a fault tolerant ac bus at a constant frequency [8,10].

Section VI

COMMON AC AND DC BUS SYSTEMS

6.1 *Common ac Bus*

Figure 6.1 shows n Schwarz modules that can be connected either in series or parallel. The main objective of this study was to determine the requirements for a monitoring system that will detect when one module is faulted and disconnect it so the other modules can continue to operate. This system has a common ac bus where each converter is driven by a common drive signal. Previous research [8,9] has shown that the current sharing between modules is very good if the L_o and C_o components are well matched. Because of the common ac bus, this arrangement could be used as the output stage of a cascaded Schwarz, constant frequency ac distribution system. It also could be used as a dc distribution system by using the single rectifier bridge to get the dc bus. In this case each converter would consist of a single stage and all converters would operate at the same variable frequency.

For a dc system, it would actually be better to have a separate rectifier bridge for each converter and connect the outputs of all the bridges in parallel as in Figure 6.2. This would allow the use of smaller rectifiers, and it would automatically isolate any converter that failed. If desired, the separate bridge arrangement also would allow a separate controller for each converter, in which case one converter would operate as the voltage regulator, and the others would operate in the current limit mode at full load.

However, the dc system would perhaps work even better by using a common control loop which would drive all converters at the same frequency. Because of their significant source impedances, the converters will share the current equally well whether they are paralleled before or after the rectifier bridge. Although both series and parallel connections of the modules were considered, it is becoming increasingly evident that only

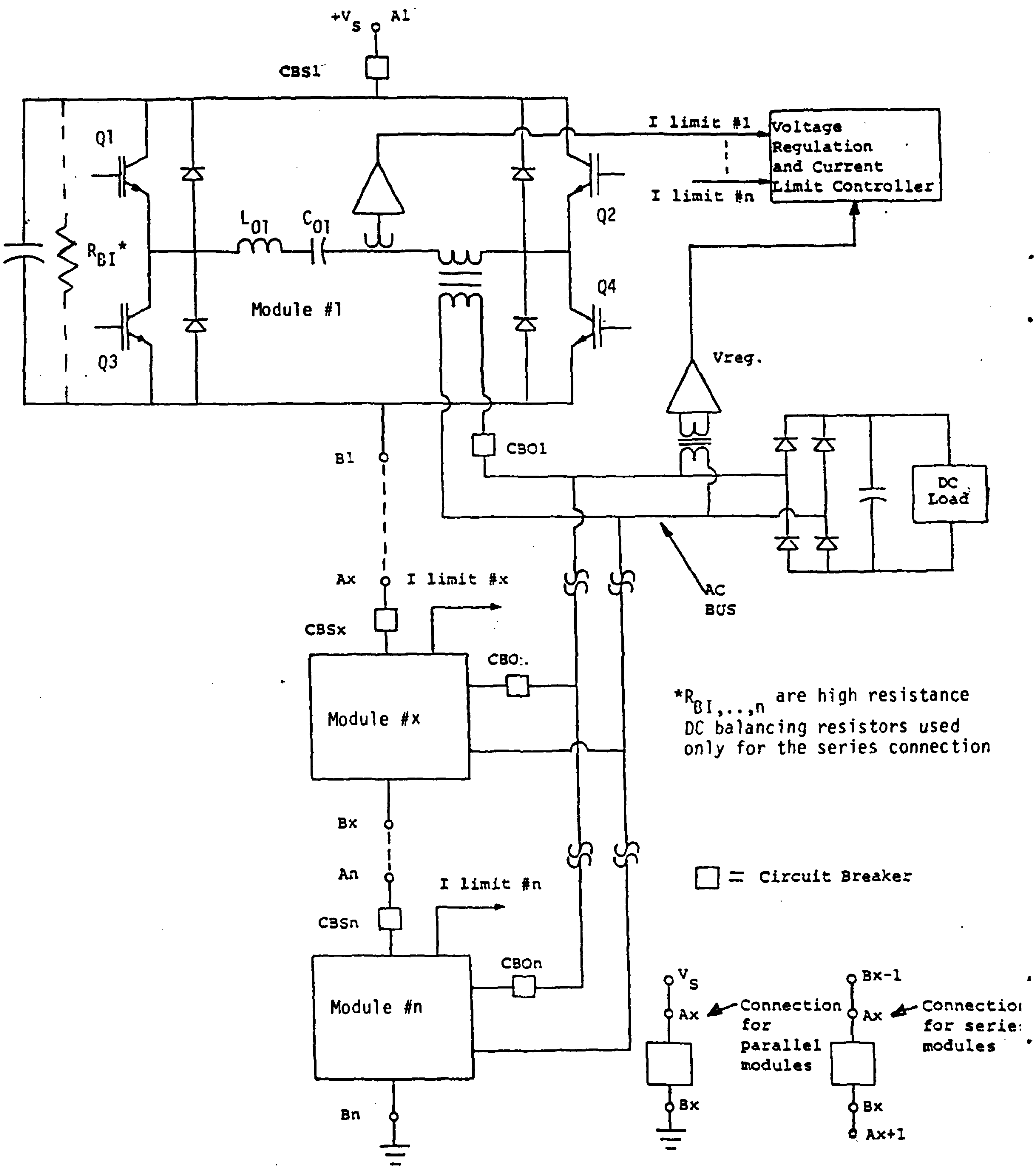


Figure 6.1: Parallel or Series Connected Converter Modules in a High Frequency dc Distribution System.

the parallel connection is likely to be used in spacecraft applications. This is because of the recent development of new switching devices that have maximum voltages in the 1000- volt range. Darlington transistors and IGBTs with 1000 V/300 A, ratings and adequate switching speeds are now available, and new MCT devices eventually may have even higher ratings. Since this is well within the expected range of a few hundred volts for spacecraft systems, there is little incentive at present to spend much effort on series module systems. Series modules also have an inherent problem in that a failed module must be short circuited to allow operation of the remaining modules. This increases the voltage across the remaining modules, and limits the number of failures that can be tolerated. Since the parallel connection appears to provide adequate voltage ratings and since the module voltages are unaffected by failures of other modules, it was decided to concentrate this study on the parallel connection.

The difficult part of designing a fault detection and isolation system is to determine which module(s) are faulted. First of all, it is absolutely necessary that each module include a fast acting current limiter such as the one indicated for module #1 in Figure 6.1. These are analog circuits that act immediately after any type of fault, and they must protect each of the modules during the time before the fault is isolated. Fortunately these limiters are fairly simple, and adequate circuits have been designed and tested. The ideal solution to the module isolation problem would be to develop a similar circuit to detect a faulted module. This may be possible for certain types of faults, but it appears unlikely that reasonably simple circuits can perform this task for the wide variety of faults that may occur.

Even for the most basic converter, such as Module #1 in Figure 6.1, the number of possible faults is enormous. Fortunately, it should be possible to develop a fairly simple fault detection/isolation system that should work for virtually any combination of faults within the module itself. To develop this strategy, it is necessary to consider the following points:

1. CBS and CBO each contain current sensors that will open the breakers if their limits are exceeded.

2. CBS and CBO should be operated together so that both trip simultaneously, e.g., if CBS opens, CBO also should open since a de-energized converter can become a large reactive load on the ac bus.

3. Since the CBS and CBO are not fast enough to protect the transistors, there are certain faults that may not be cleared by the current sensors in these breakers. One of the most serious examples is where Q1 and Q2 fail short while Q3 and Q4 fail open. This de-energizes the module and connects L_o-C_o in parallel with the ac bus, which becomes a large reactive load. It could be argued that this type of fault is unlikely since high power semiconductors tend to fail as short circuits, which would trip CBS. It seems inadvisable to depend on this however, meaning that the system should be capable of detecting and isolating faults that include both open and short circuits. This reactive load dissipates very little power itself, but the higher reactive currents will limit the available power for the rest of the system. This is probably not a serious condition, unless the reactive load is high enough to place the system in the current limit mode which lowers the ac bus voltage. If this occurs, a computer monitor can remove each module one-at-a-time until it detects either an increase or no change in the bus voltage, which indicates the last module removed is the bad one. If removal of the bad module does not restore the voltage, a system overload is indicated and some load must be shed as well.

6.2 *Common dc Bus*

The same strategy used for protecting the common ac bus system in Figure 6.1 applies to the common dc bus system in Figure 6.2, except that each rectifier bridge will isolate a converter fault without opening the CBO breaker. The CBO breakers are still needed however for isolating faults in the output capacitors or rectifiers.

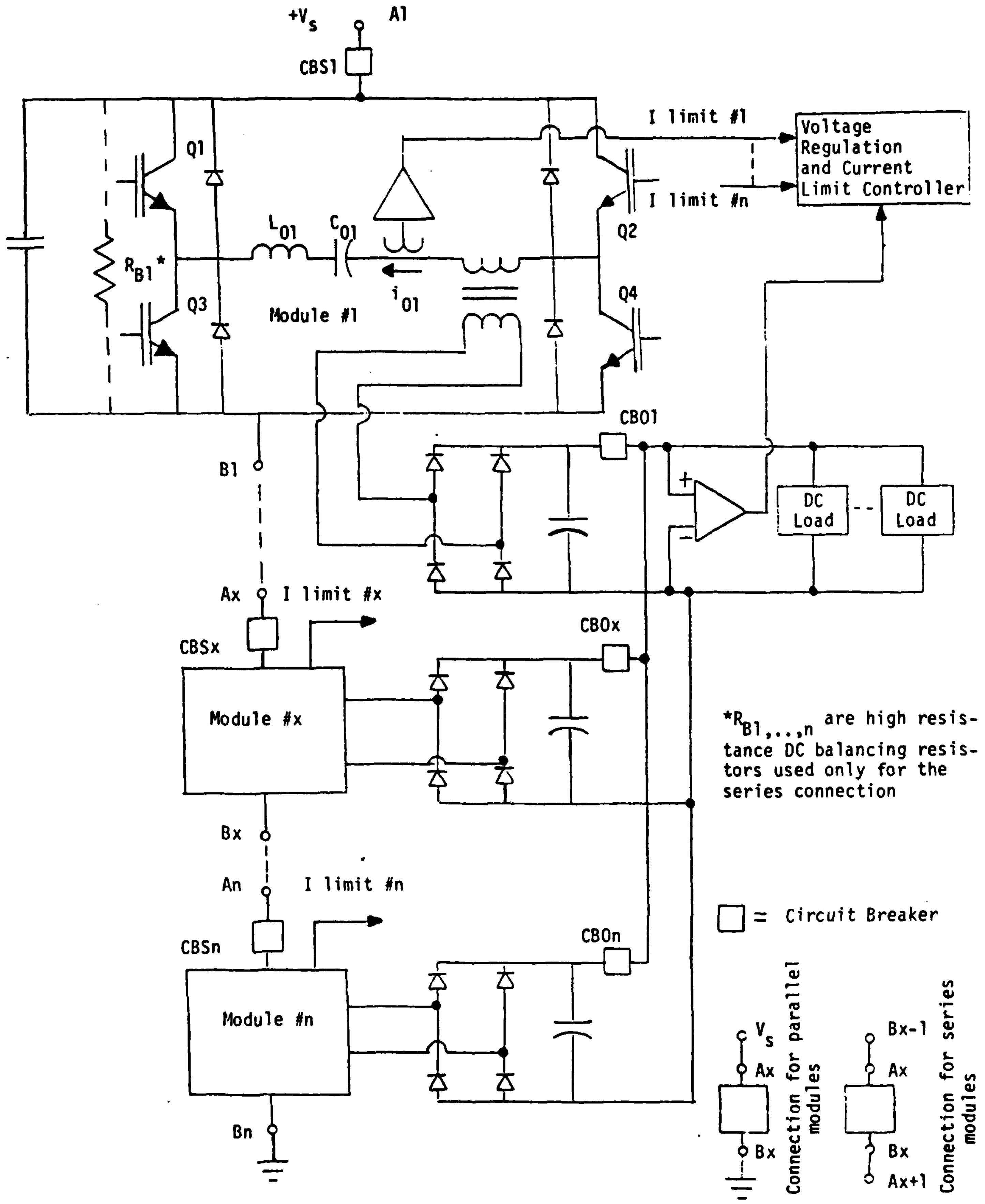


Figure 6.2: Parallel or Series Connected Converter Modules in a dc Distribution System.

Section VII

EXPERIMENTAL RESULTS FOR PART II

Section VI describes a strategy for a computer controlled system that could be used to isolate faulted converter modules for systems that use either a common ac bus or a common dc bus. A series of tests were performed on a common ac bus system to evaluate the feasibility of this strategy.

These tests were performed on the single phase cascaded Schwarz converter with three parallel output stages which is shown in Appendix A. The three converters are designated as A, B and C. Figsures 7.1 and 7.2 show the output current waveforms for all three converters before and after faults were applied. These figures indicate that all three were initially well balanced.

Figure 7.3 is for the same load resistor as Figure 7.1 expect Q3 of B is open. The output is now V_o = 172 VDC, I_o = 10.3 Adc since the load is too large for converters A and C and both are in the current limit mode. Figure 7.4 is the same as Figure 7.3 except 33% of the load has been shed, and the output voltage has been restored to 204.7 Vdc.

Figure 7.5 is for almost the same load resistor as Figures 7.1, 7.2 and 7.3 except both Q1 and Q3 of B are open. Figure 7.6 is the same as Figure 7.5 except that 33% of the load has been shed to restore the output to 202.8 Vdc.

Figure 7.7 is for the same full load resistance as Figures 7.1, 7.2, 7.3 and 7.5 except Q1 and Q2 of B are shorted while Q3 and Q4 of B are open. As noted earlier, this is one of the more serious fault conditions, and it might occur since the transistors will usually fail before the CBS-CBO breakers can open. Figures 7.7-7.9 show the output currents for full load, 66% load, and 33% load, respectively. As noted by the data presented with the figures, the full output of 204 Vdc was never reached and the system remained in the current limit mode for all three loads. It should be noted that even though the B converter is inoperable,

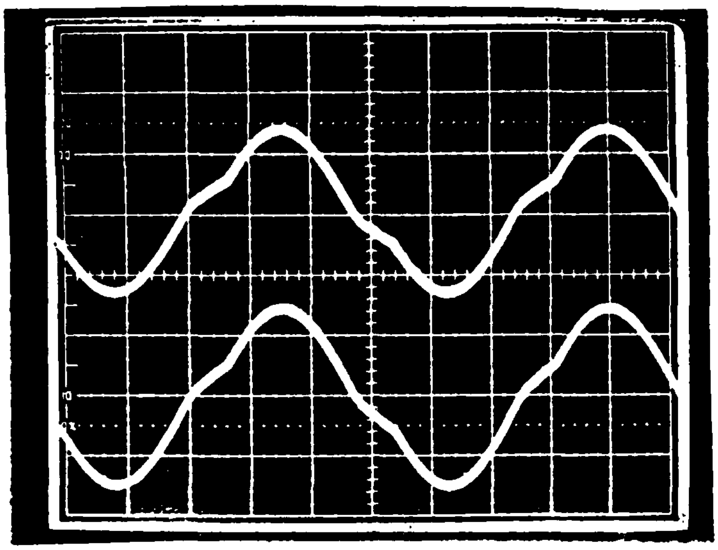


Figure 7.1. Top: i_{oB}, 5 A/cm
Bot: i_{oA}, 5 A/cm
Horiz. = 10 μs/cm., V_o = 204.4 Vdc, I_o = 12.1 Adc

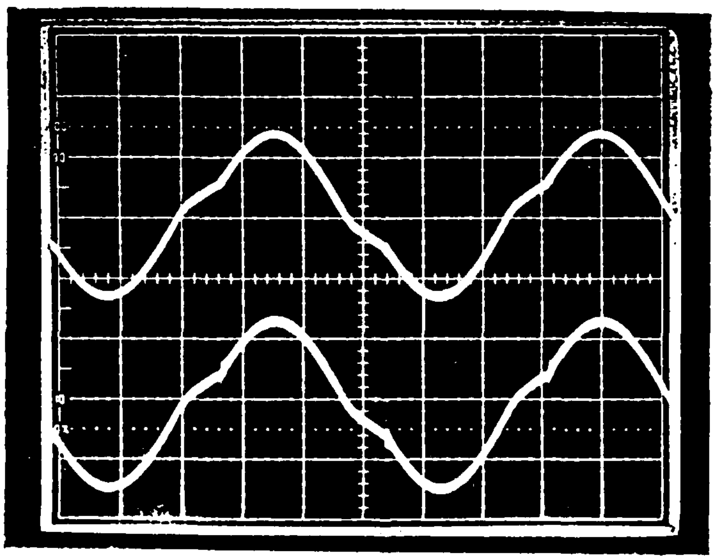


Figure 7.2. Top: i_{oB}, 5 A/cm
Bot: i_{oC}, 5 A/cm
Horiz. = 10 μs/cm., V_o = 204.4 Vdc, I_o = 12.1 Adc

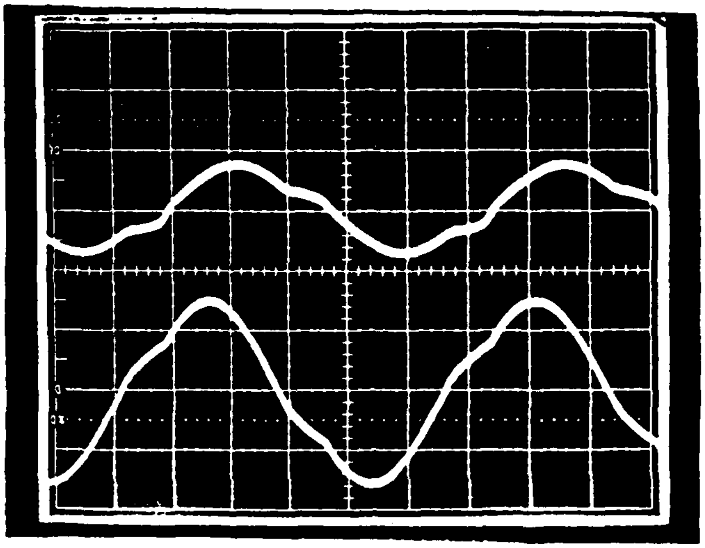


Figure 7.3. Top: i_{oB}, 5 A/cm
Bot: i_{oA}, 5 A/Cm
Horiz. = 10 μs/cm., V_o = 172 Vdc, I_o = 10.3 Adc
Same load as Figures 7.1 and 7.2, but Q3 of B = open

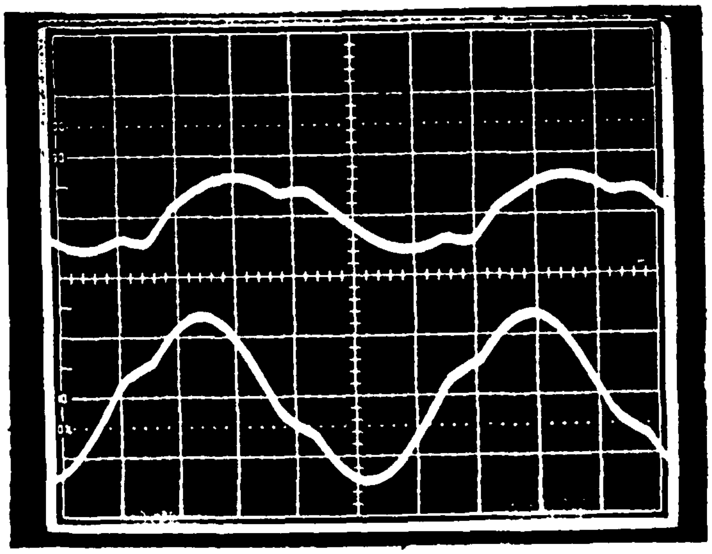


Figure 7.4. Top: i_{oB}, 5 A/cm
Bot: i_{oA}, 5 A/cm
Horiz. = 10 μs/cm., V_o = 204.7 Vdc, I_o = 8.7 Adc
Same as Figure 7.3 but with 33% load shed. Q3 of B = open

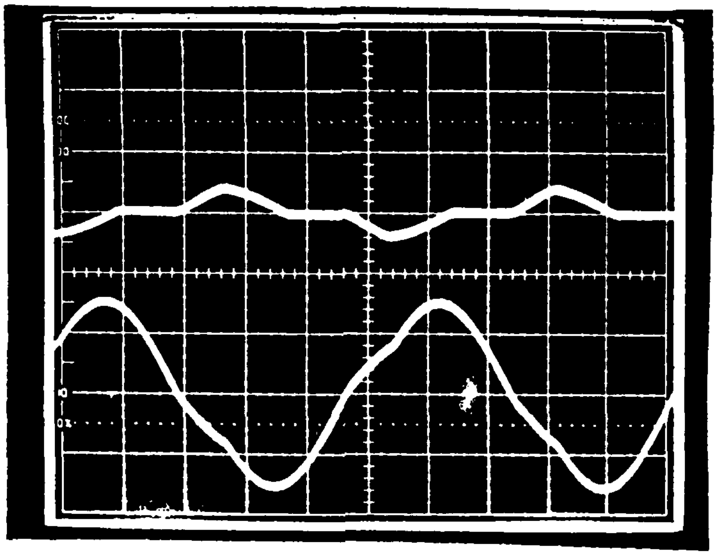


Figure 7.5. Top: i_{oB}, 5 A/cm
Bot: i_{oA}, 5 A/cm
Horiz. = 10 μs/cm., V_o = 154 Vdc, I_o = 8.04 Adc
Same load as Figures 7.1 and 7.2, but Q1 and Q3 of B = open

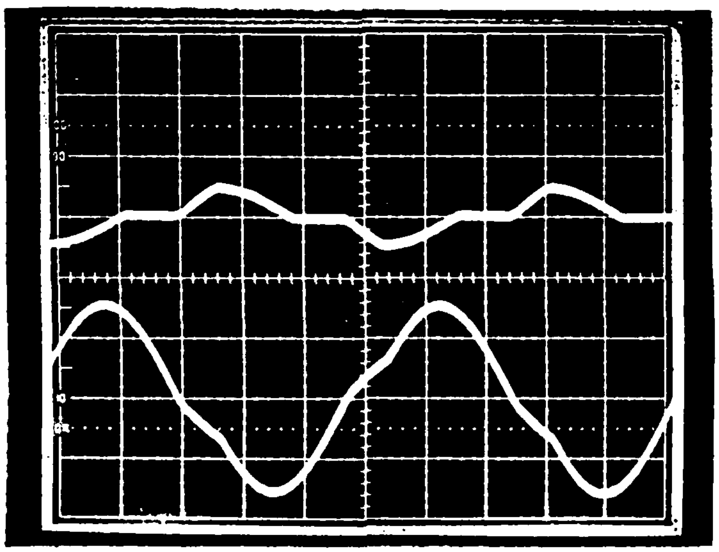


Figure 7.6. Top: i_{oB}, 5 A/cm
Bot: i_{oA}, 5 A/cm, V_o = 203 Vdc, I_o = 7.76 Adc
Same as Figure 7.5 but with 33% load shed.

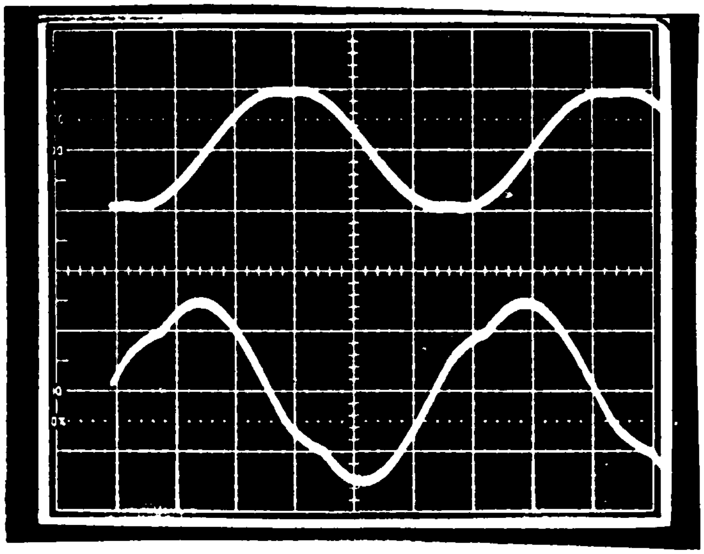


Figure 7.7. Top: i_{oB}, 5 A/cm
Bot: i_{oA}, 5 A/cm
Horiz. = 10 µs/cm., V_o = 137 Vdc, I_o = 8.2 Adc
Same load as Figures 7.1 and 7.2, but Q1 and Q2 of B = short and Q3 and Q4 of B = open

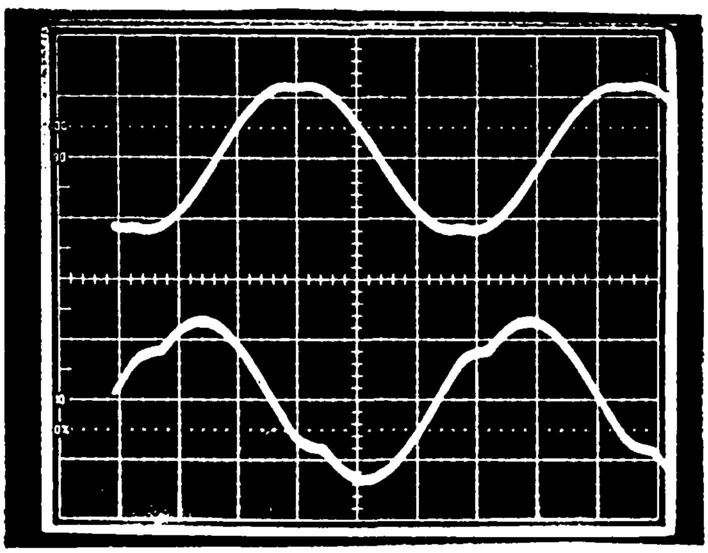


Figure 7.8. Top: i_{oB}, 5 A/cm
Bot: i_{oA}, 5 A/cm
Horiz. = 10 µs/cm., V_o = 172 Vdc, I_o = 6.72 Adc
Same as Figure 7.7 but with 33% load shed

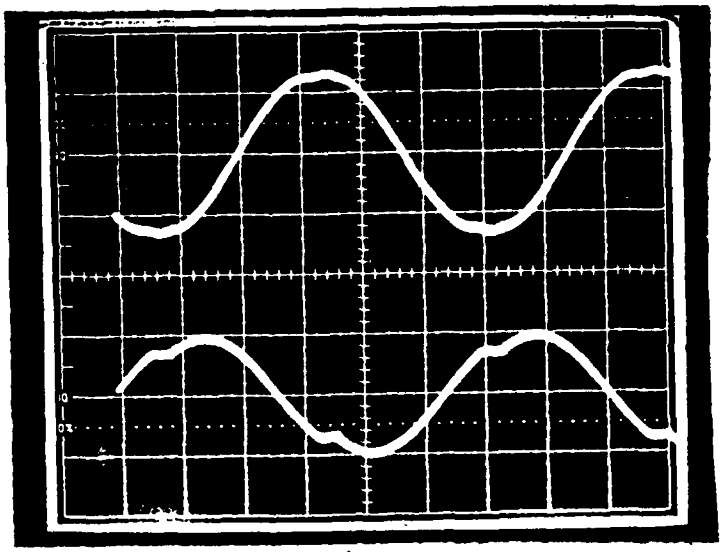


Figure 7.9. Top: i_{oB}, 5 A/cm
Bot: i_{oA}, 5 A/cm
Horiz. = 10 μs/cm., V_o = 142 Vdc, I_o = 3.64 Adc
Same as Figure 7.7 but with 66% of load shed

its current limit loop is still active, and it can act to limit the system current the same as the current loops of the A and C converters. This is perfectly acceptable, however, and the proposed fault detection and isolation system could still identify the bad converter since the output voltage would increase when CBO of B was opened.

Section VIII

CONCLUSIONS FOR PART II

These preliminary results indicate that it should be feasible to implement a fault detection and isolation system for a series of Schwarz converter modules operating in parallel. Although this system would be computer controlled, it is fairly simple in concept and uses the method of sequentially disconnecting modules until the bad one is found. The experimental tests performed here indicate that it should be possible to detect faults in this manner, and the next step would be to build and test a computer controlled demonstration system.

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Appendix A

SINGLE PHASE PARALLEL MODULE CASCADED SCHWARZ CONVERTER SCHEMATICS

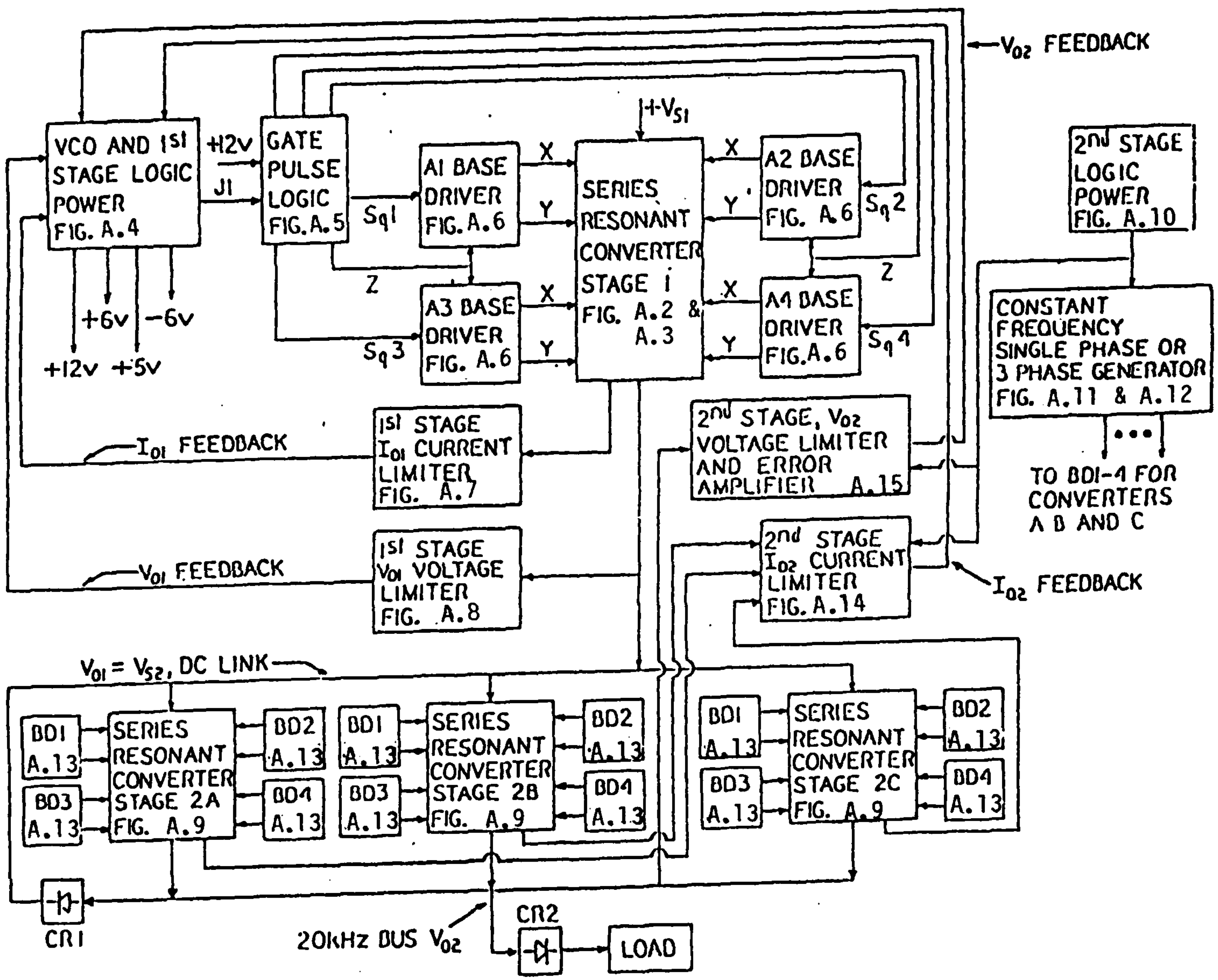

Figure A.1: Single Phase Parallel Module Cascaded Schwarz Converter Block Diagram.

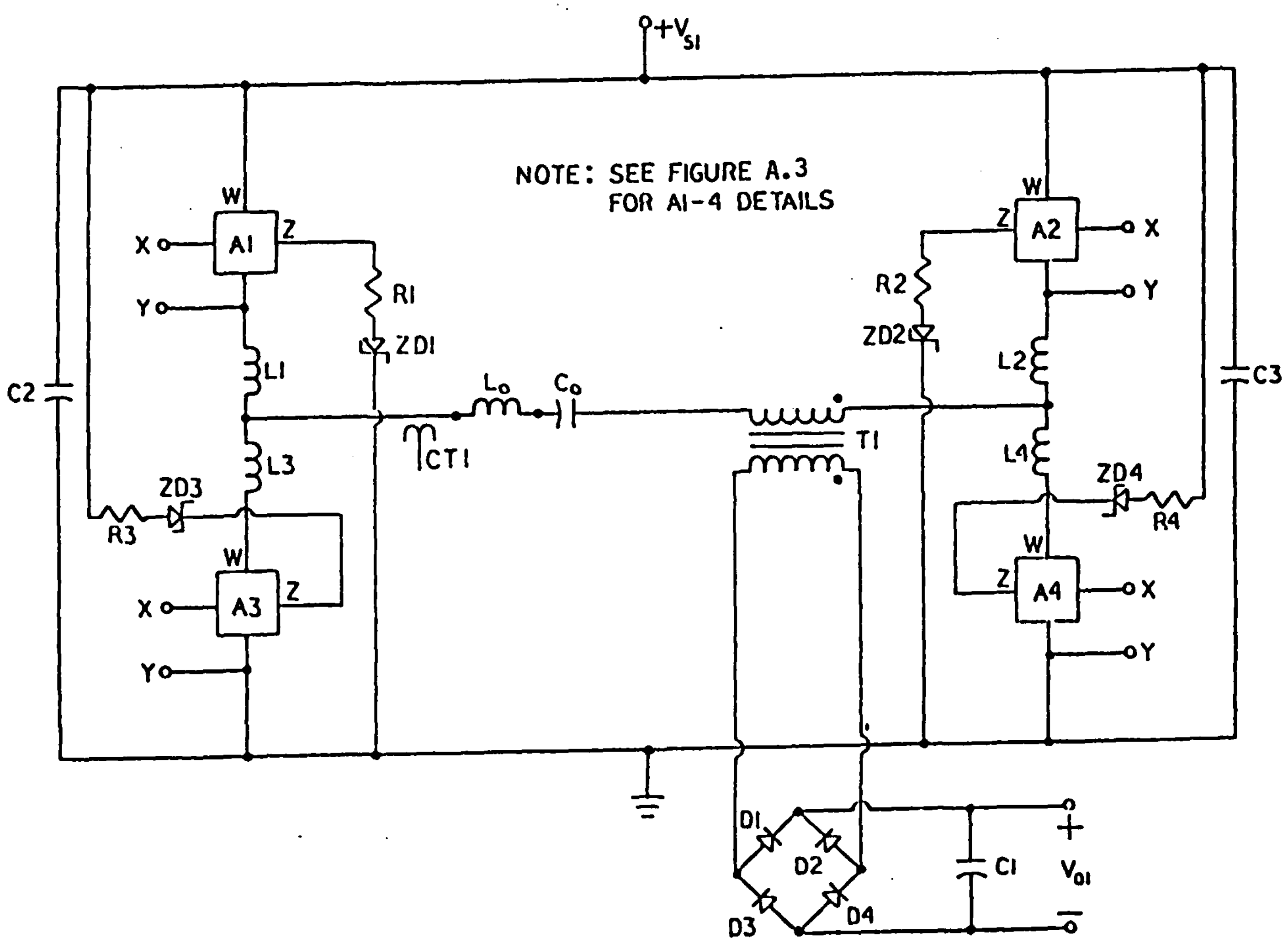

Figure A.2: Stage 1 Variable Frequency Series Resonant Conveter.

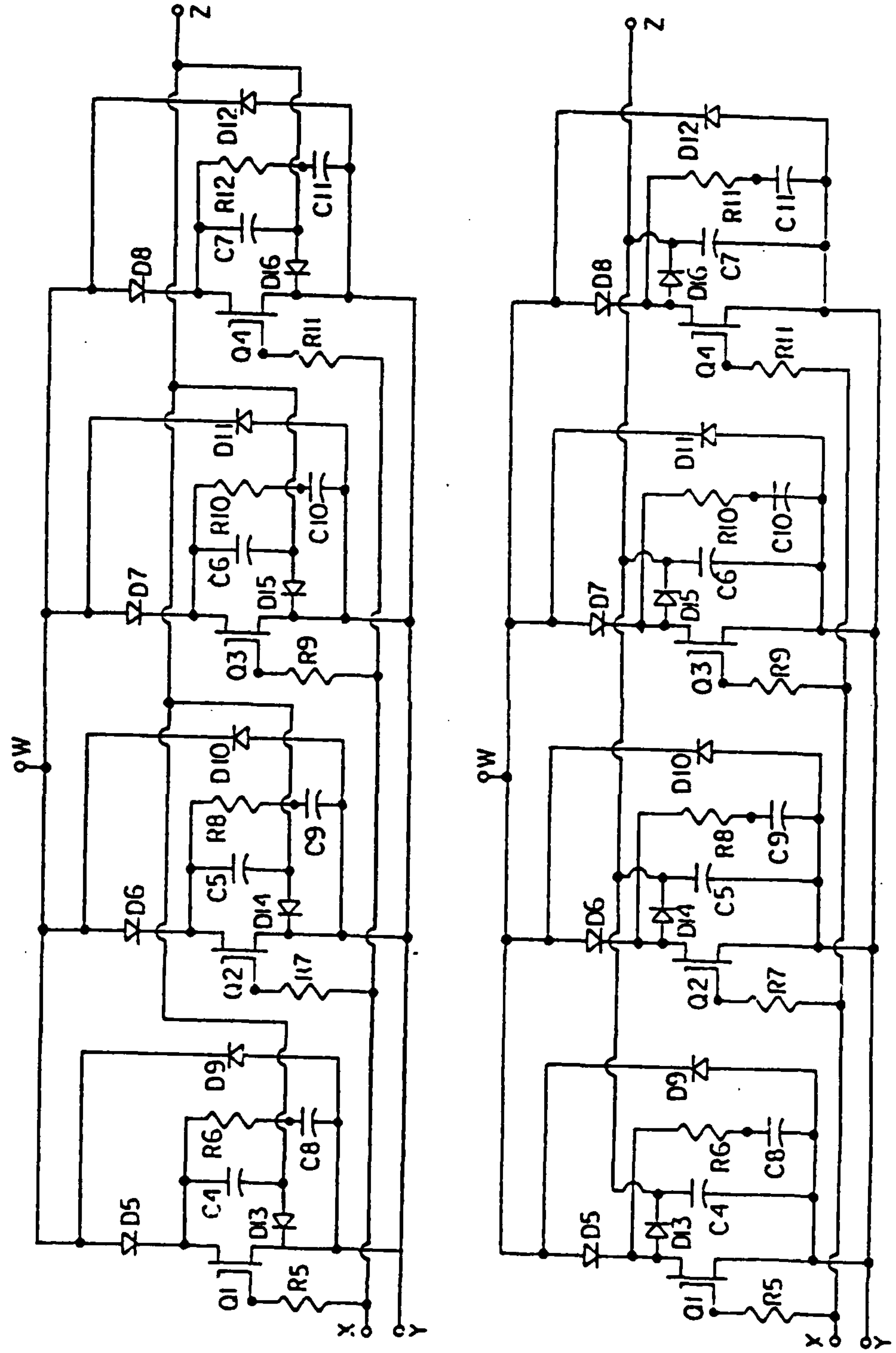

Figure A.3: Top - Blocks A1 and A2. Bottom - Blocks A3 and A4.

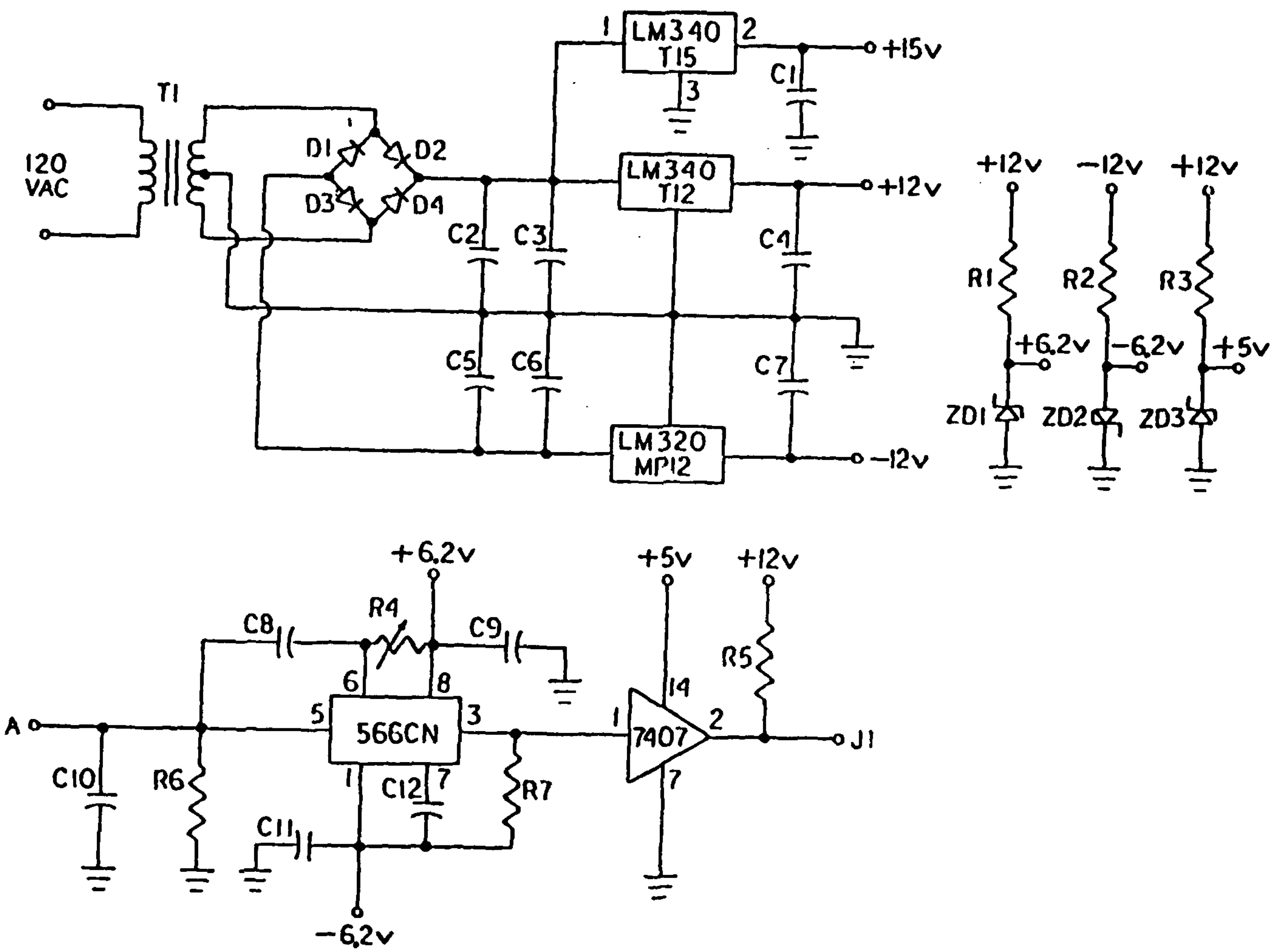

Figure A.4: VCO and Stage 1 Logic Power Supply.

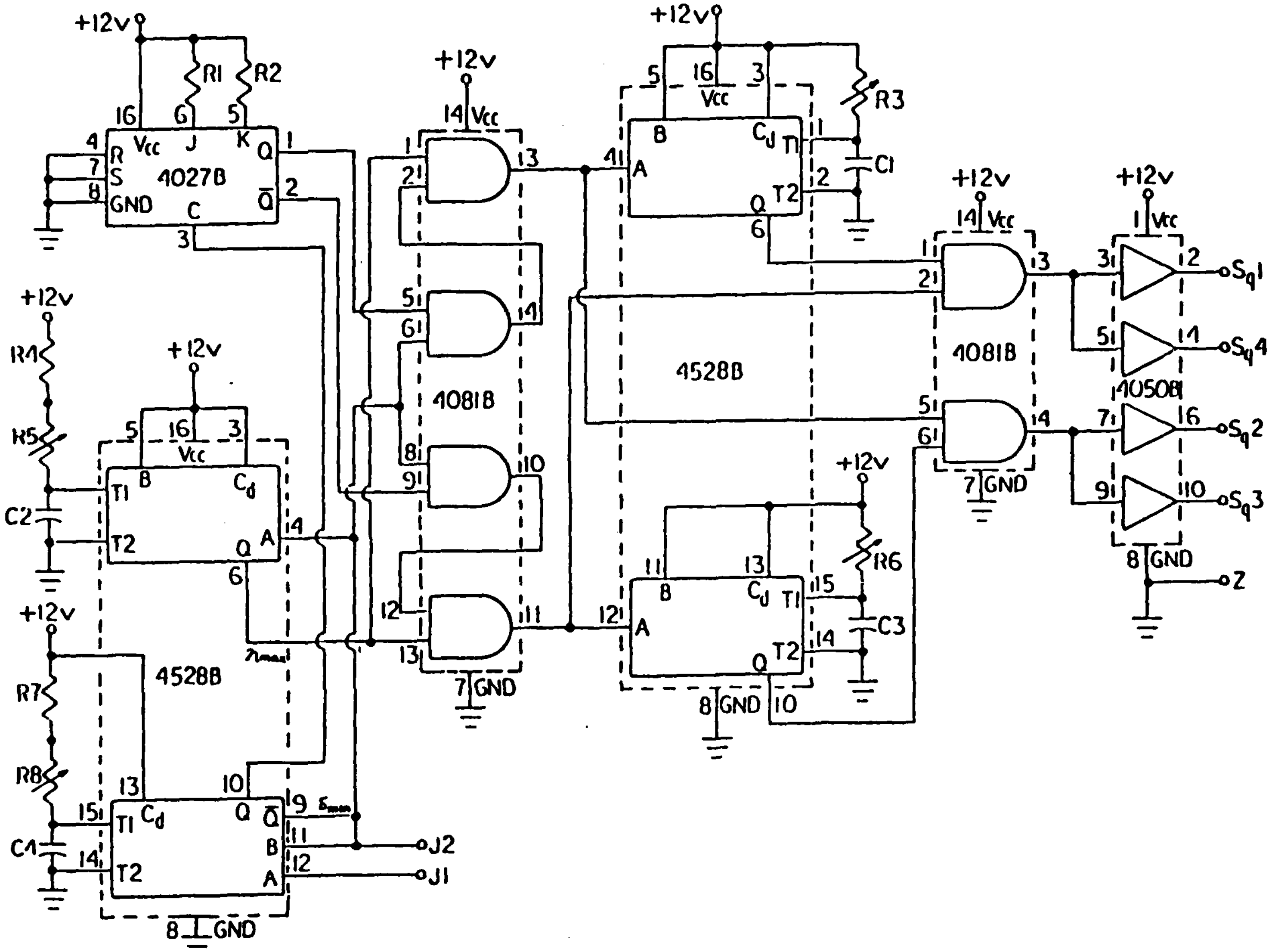

Figure A.5: Stage 1 Gate Pulse Logic.

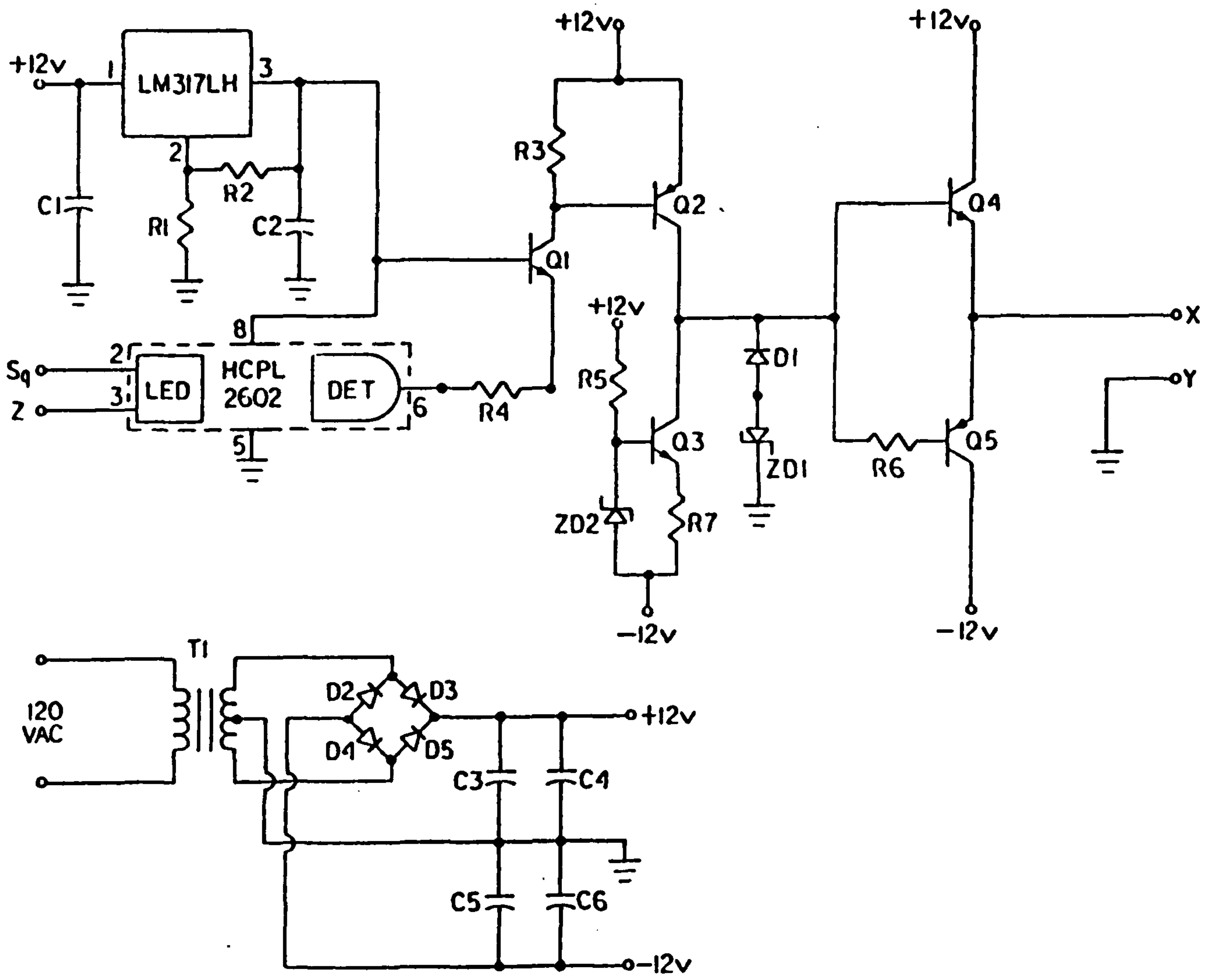

Figure A.6: Stage 1 MOSFET Transistor Base Drive.

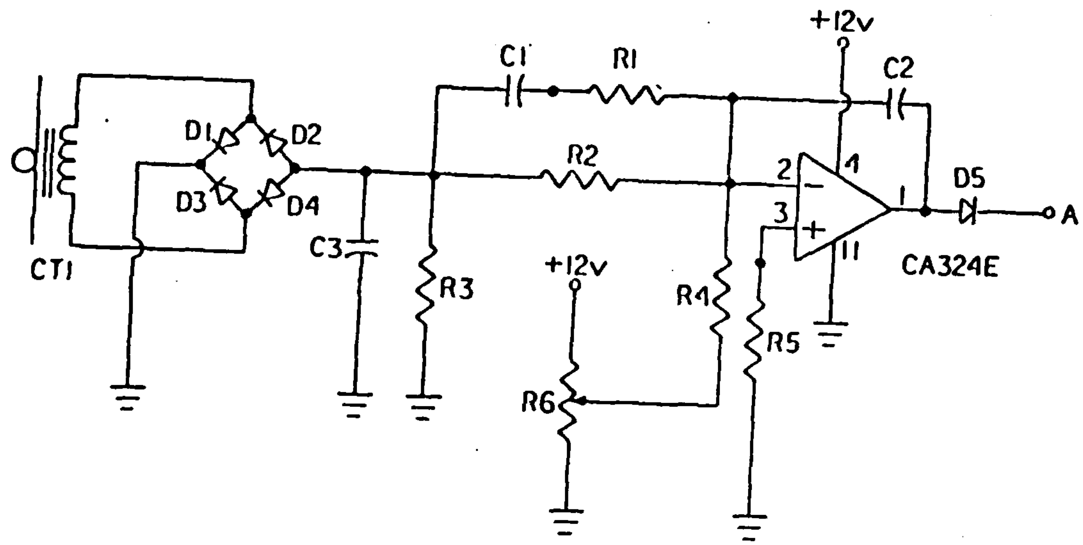

Figure A.7: Stage 1 Output Current Limiter.

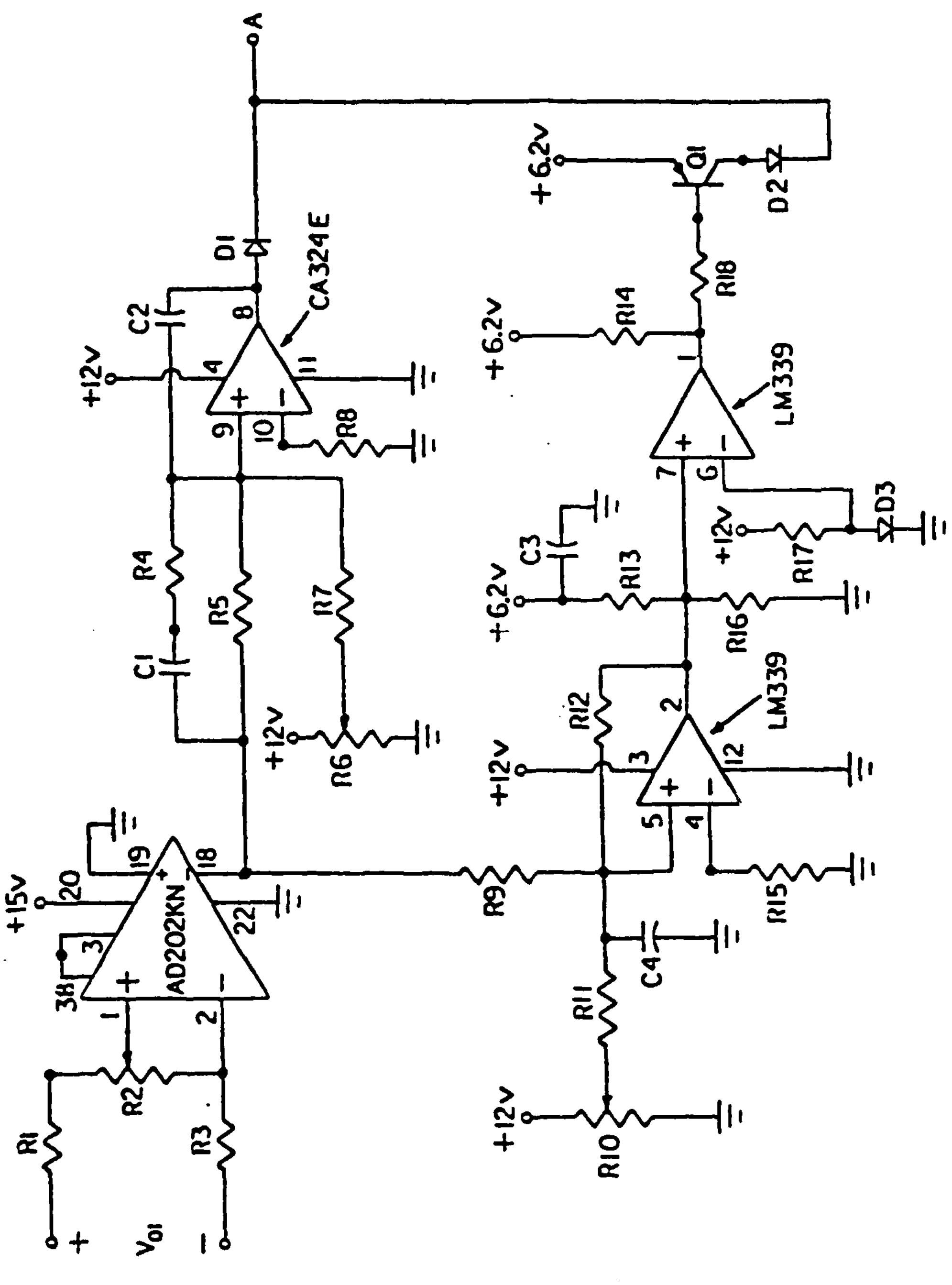

Figure A.8: Stage 1 Voltage Limiter.

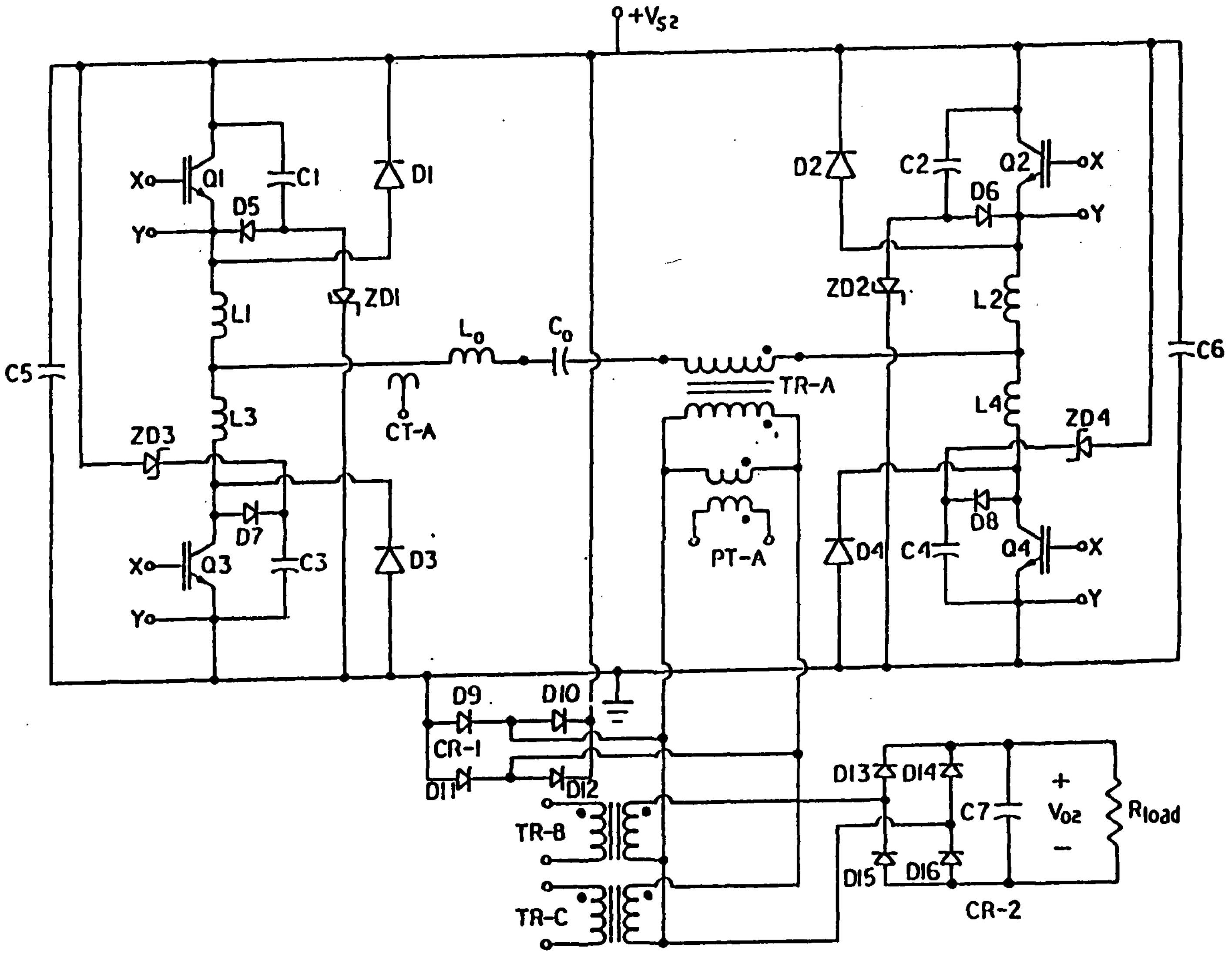

Figure A.9: Stage 2 - Module A Series Resonant Inverter, Connections to Modules B and C, Typical Load Rectifier CR-2 and Recycling Rectifier CR-1.

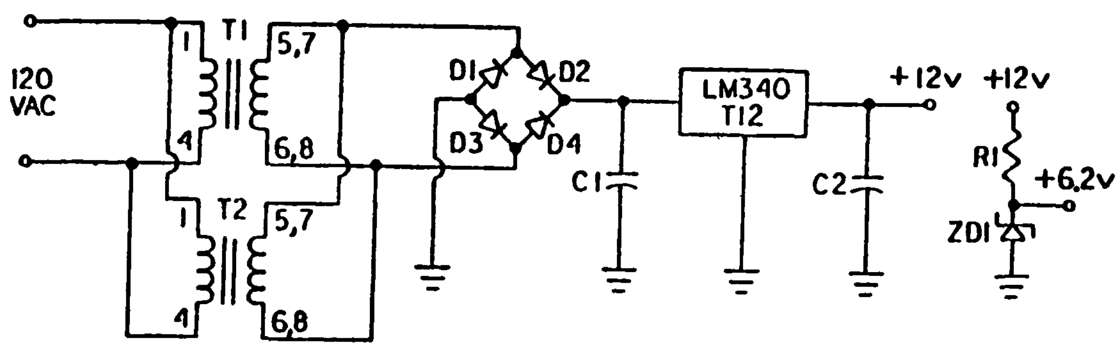

Figure A.10: Stage 2 Logic Power Supply.

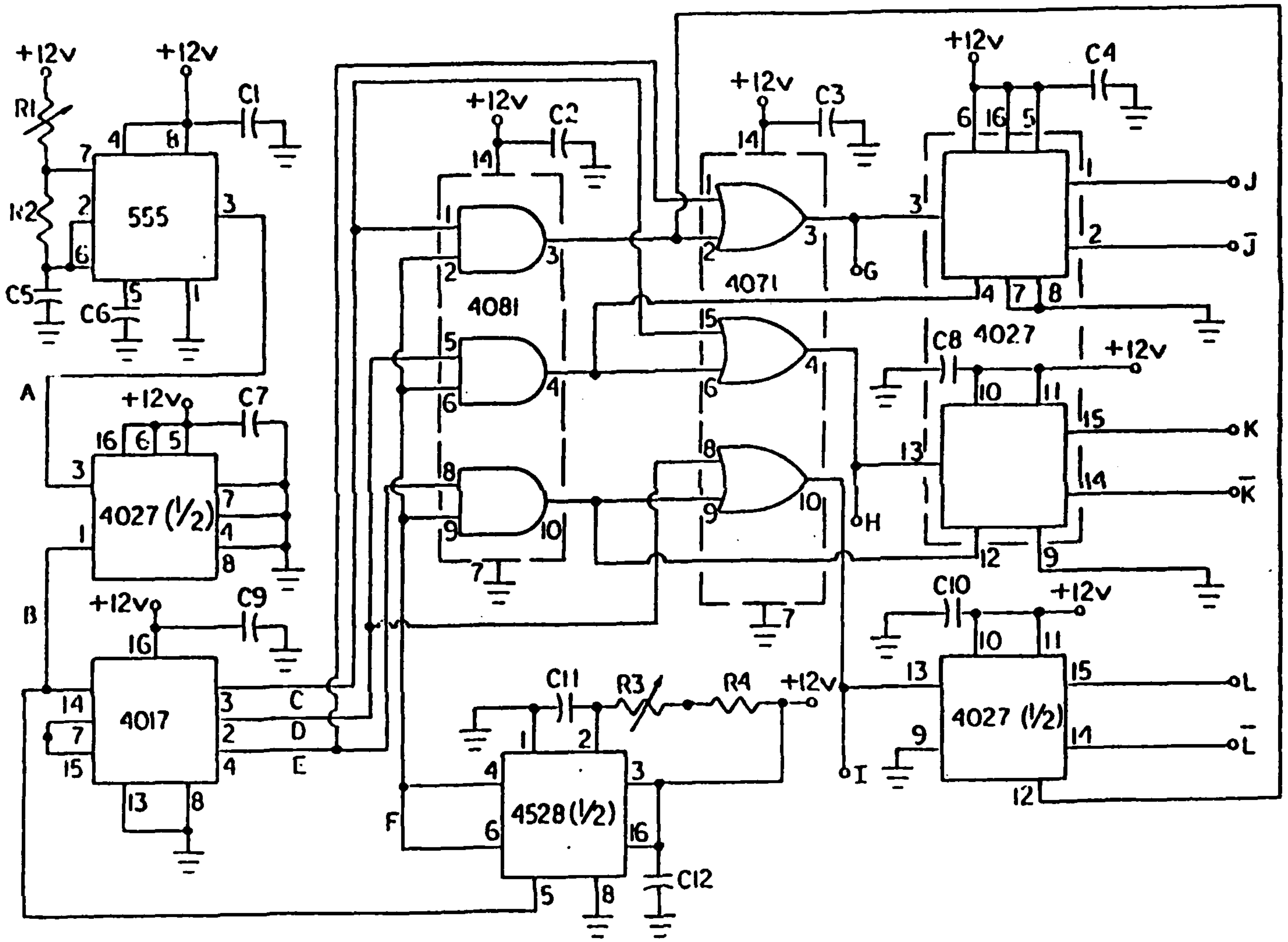

Figure A.11: Stage 2 Constant Frequency Single Phase or Three Phase Generator.

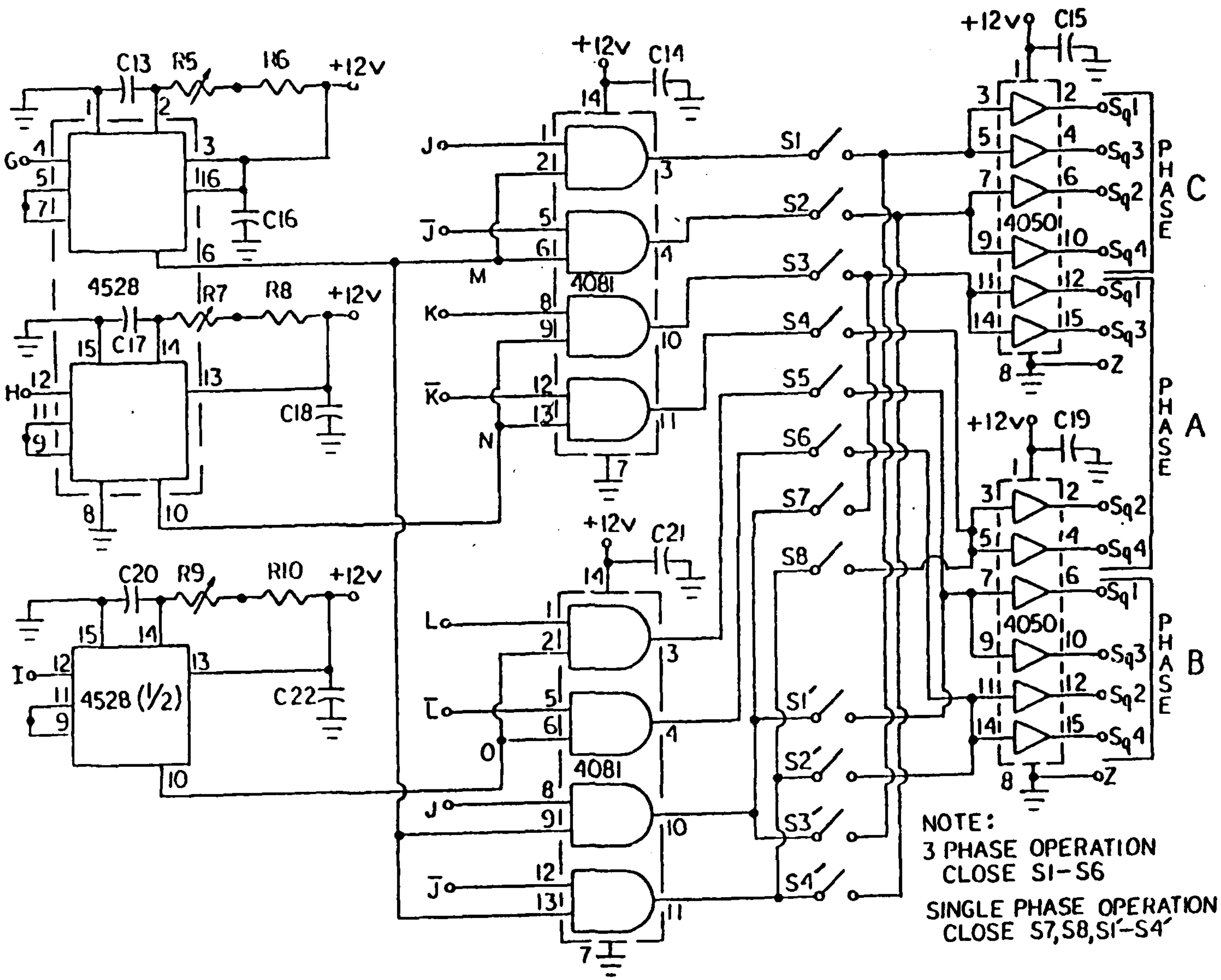

Figure A.12: Stage 2 Constant Frequency Single Phase or Three Phase Generator (continued).

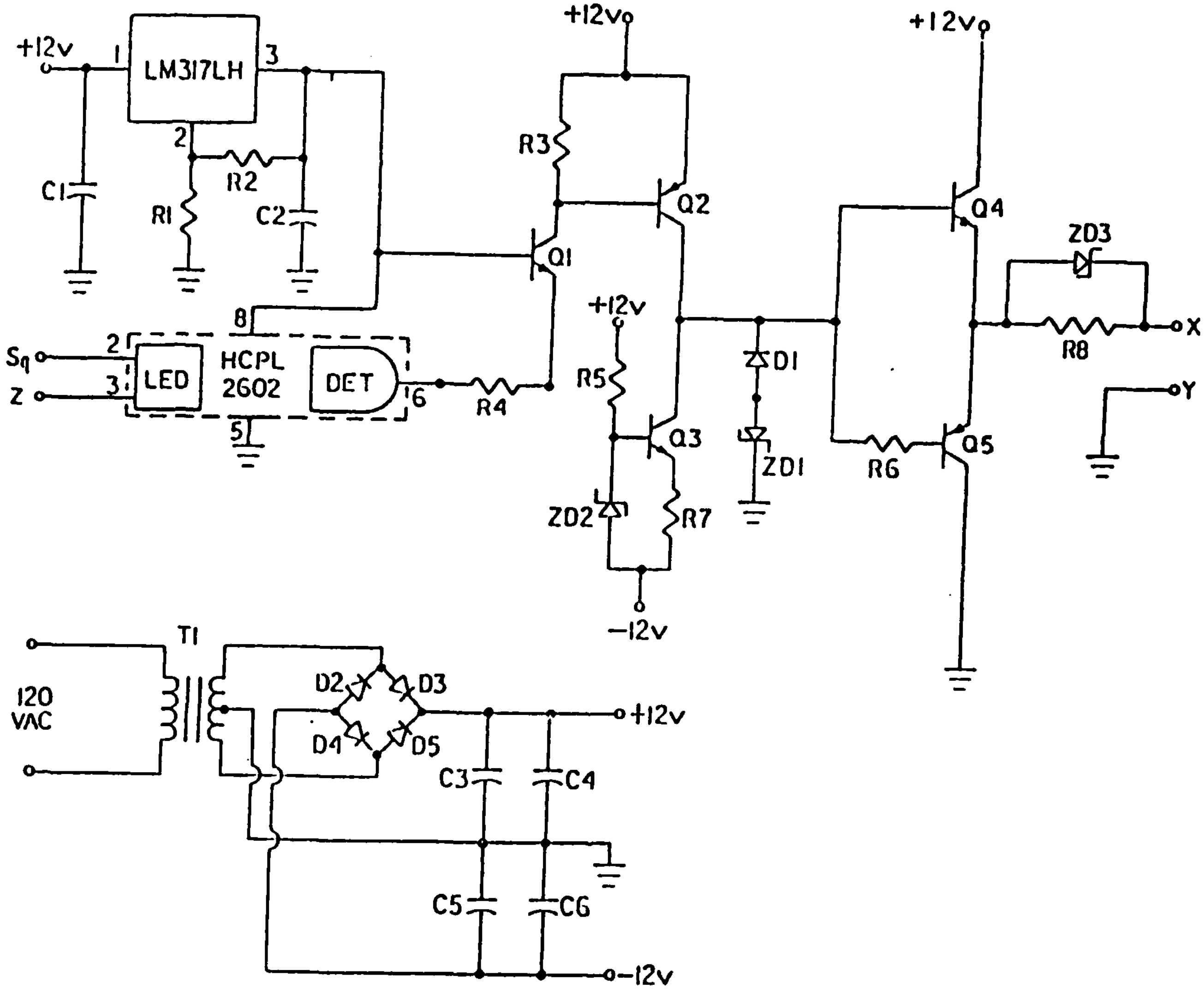

Figure A.13: Stage 2 Modules A, B and C Insulated Gate Transistor Base Drive.

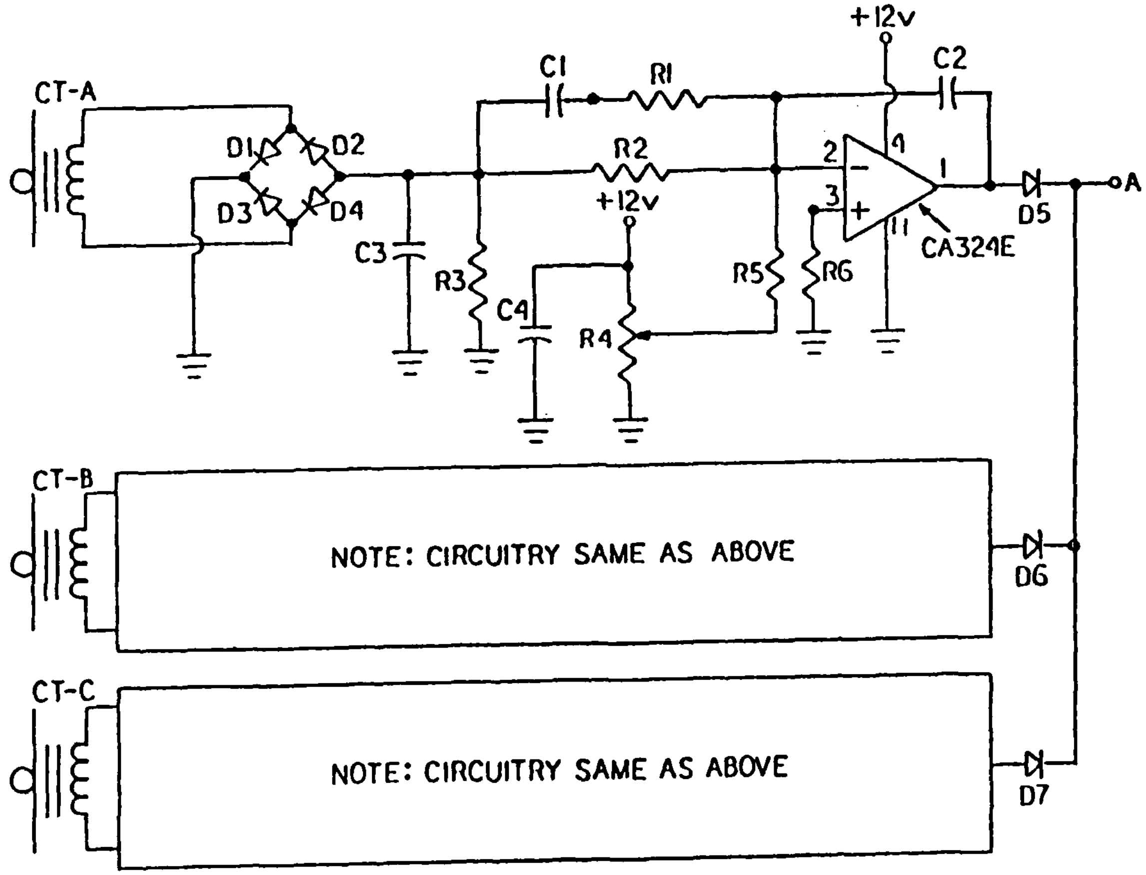

Figure A.14: Stage 2 Output Current Limiter.

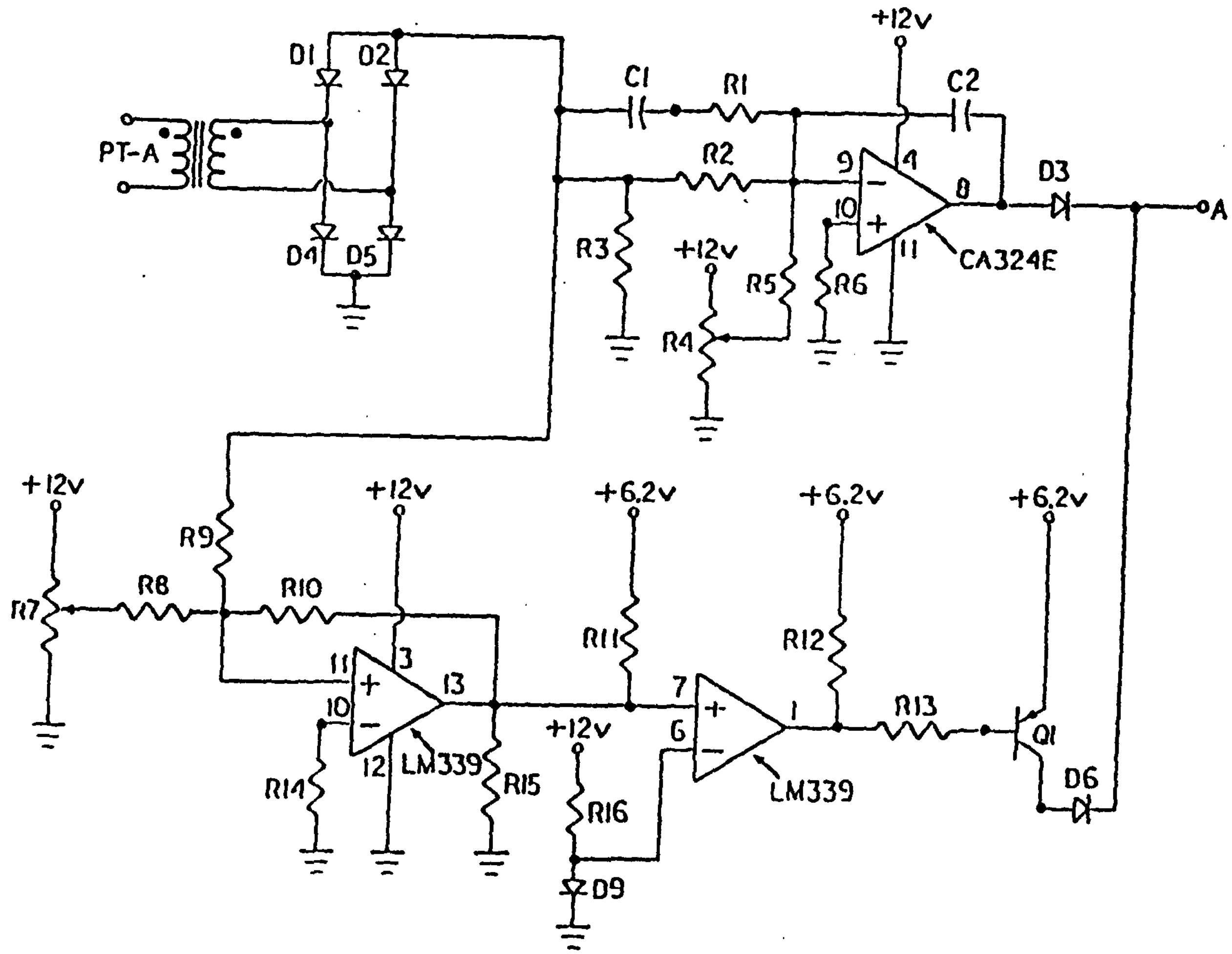

Figure A.15: Stage 2 Voltage Limiter and Error Amplifier.

Table A.1: 2500-watt SPPM Cascaded Schwarz Converter Parts List

Figure A.2: Stage 1 Variable Frequency Series Resonant Converter.

Capacitors:	
C_o	1.24 μF
C1	0.270 μF
C2, C3	0.20 μF (polypropolene)
Diodes:	
D1-D4	MR1386
Zener Diodes:	
ZD1-ZD4	1N2819A
Resistors:	
R1-R4	2.2 Ω 3 Watt
Inductors:	
L_o	45.0 μH
L1-L4	4.0 μH
Transformers:	
T1	Np = 32 turns, 16 strands 50/36 litz Ns = 164 turns, 3 strands 50/36 litz Ferrite core
CT1	Np = 1 turn, 8 strands 36/50 litz Ns = 210 turns, #24 magnet wire 4229 Ferrite core

Figure A.3; Top - Blocks A1 and A2. Bottom - Blocks A3 and A4.

Capacitors:	
C4-C7	0.033 μF
C8-C11	0.0022 μF
Diodes:	
D5-D8	1N5829
D9-D12	1N3911
D13-D16	MR824
Resistors:	
R5,R7,R9,R11	27.0 Ω 1/2 Watt
R6,R8,R10,R12	100.0 Ω 5.0 Watt
Transistors (MOSFETS):	
Q1-Q4	MTM404N20

Table A.1 (cont'd.)

Figure A.3; VCO and Stage 1 Logic Power Supply.

Capacitors:	
C1,C4,C7,C10	0.1 μF
C2,C5	100.0 μF
C3,C6	224.0 μF
C8	0.001 μF
C9, C11	0.47 μF
C12	0.01 μF
Diodes:	
D1-D4	1N4005
IC Chips:	
LM320MP12	
LM340T12	
LM340T15	
566CN	
7407	
Resistors:	
R1-R3	270.0 Ω
R4	5.0 $k\Omega$ trimpot
R5	10.0 $k\Omega$
R6	100.0 $k\Omega$
R7	4.7 $k\Omega$
Transformers:	
T1	Signal Transformer ST-3-36

Figure A.5; Gate Pulse Logic.

Capacitors:	
C1,C2	200.0 pF
C3,C4	0.047 μF
IC Chips:	
CD4027B	
CD4050B	
MC1 4528B	
SC14801A	
Resistors:	
R1,R2	1.0 $k\Omega$
R3	47.0 $k\Omega$
R4	100.0 $k\Omega$ trimpot
R5	10.0 $k\Omega$
R6	10.0 $k\Omega$ trimpot
R7,R8	100.0 $k\Omega$

Figure A.6; Stage 1 MOSFET Transistor Base Drive.

Capacitors:	
C1,C2	0.1 μF

Table A.1 (cont'd.)

C3-C6	2200.0 μF
Diodes:	
D1	1N4935
D2-D5	1N4005
Zener Diodes:	
ZD1	1N4733
ZD2	1N4731
IC Chips:	
LM317LH	
HP2602	
Resistors:	
R1	1.2 kΩ
R2	330.0 Ω
R3	470.0 Ω
R4	830.0 Ω
R5	1.0 kΩ
R6	82.0 Ω
R7	47.0 Ω
R8	20.0 Ω 1/2 Watt
Transformer:	
T1	Signal Transformer ST-5-16
Transistors:	
Q1	2N4401
Q2	2N4036
Q3	2N2102
Q4	D40D1
Q5	D41D1

Figure A.7; Stage 1 Output Current Limiter.

Capacitors:	
C1	0.047 μF
C2	0.033 μF
C3	0.47 μF
Diodes:	
D1-D5	1N4148
IC Chips:	
CA324E	
Resistors:	
R1	56.0 kΩ
R2,R4	100 kΩ
R3	220.0 Ω
R5	27.0 kΩ
R6	10.0 kΩ trimpot

Table A.1 (cont'd.)

Transformer:	
CT1	Np - 1 turn, 8 strands 36/50 litz Ns - 240 turns, #24 magnet wire 4229 Ferrite core

Figure A.8; Stage 1 Voltage Limiter.

Capacitors:	
C1	0.047 μF
C2	0.033 μF
C3	330.0 pF
Diodes:	
D1-D3	1N4148
Resistors:	
R1,R3	560.0 $k\Omega$
R2	20.0 $k\Omega$
R4,R8,R15	56.0 $k\Omega$
R5,R7,R9,R11	100.0 $k\Omega$
R6,R10	10.0 $k\Omega$ trimpot
R12	1.0 $M\Omega$
R13,R14,R16,R18	10.0 $k\Omega$
R17	20.0 $k\Omega$
Transistor:	
Q1	2N4403

Figure A.10; Stage 2 - Module A Series Resonant Inverter, Connections to Modules B and C, Typical Load Rectifier CR-2 and Recycling Rectifier CR-1.

Capacitors:	
C_o	0.0656 μF
C1-C4	0.047 μF
C5,C6	10.0 μF
C7	270.0 μF
Diodes:	
D1-D4	MUR840
D5-D8	MR916
D9-D20	MR1386
Zener Diodes:	
ZD1-ZD4	1N3028B
Inductors:	
L_o	1.05 mH
L1-L4	11.3 μH
Transformers:	
CT-A	Np - 1 turn, #12 magnet wire Ns - 200 turns, #28 magnet wire

Table A.1 (cont'd.)

	2616 Ferrite pot core
PT-A	Np = 200 turns, #28 magnet wire Ns = 5 turns, #28 magnet wire 3622 Ferrite pot core
TR-A,B,C	Np=Ns = 76 turns, 1 strand 36/50 litz (38 turns/spool) IG69.85 Ferrite E-core
Transistors:	
Q1-Q4	IGT4D10

Figure A.10: Stage 2 Logic Power Supply.

Capacitors:	
C1	1000.0 μF
C2	0.1 μF
Diodes:	
D1-D4	1N4007
Zener Diodes:	
ZD1	1N5234
IC Chips:	
LM340T12	
Resistors:	
R1	270.0 Ω
Transformers:	
T1,T2	Signal Transformer ST-3-36

Figure A.11 and A.12; Stage 2 Constant Frequency Single Phase or Three Phase Generator.

Capacitors:	
C1-C4,C7-C10,C14-C16 C18,C19,C21,C22	0.1 μF
C5,C13,C17-C20	0.0033 μF
C6	0.01 μF
C11	10.0 pF
IC Chips:	
NE555	
4017	
4027	
4050	
4071	
4081	
4528	

Table A.1 (cont'd.)

Resistors:

R1	1.0 $k\Omega$ trimpot
R2	1.6 $k\Omega$
R3,R5,R7,R9	10.0 $k\Omega$ trimpot
R4	15.0 $k\Omega$
R6,R8,R10	10.0 $k\Omega$

Switches:
8 pin Dip Switch
4 pin Dip Switch

Figure A.13: Stage 2 Modules A, B and C Insulated Gate Transistor Base Drive.

Capacitors:

C1,C2	0.1 μF
C3-C6	2200.0 μF

Diodes:

D1	1N4935
D2-D5	1N4005

Zener Diodes:

ZD1	1N4733
ZD2	1N4731
ZD3	1N4734A

IC Chips:
LM317LH
HP2602

Resistors:

R1	1.2 $k\Omega$
R2	330.0 Ω
R3	470.0 Ω
R4	830.0 Ω
R5	1.0 $k\Omega$
R6	47.0 Ω
R7	82.0 Ω
R8	100.0 Ω 1/2 Watt

Transformer:

T1	Signal Transformer ST-5-16

Transistors:

Q1	2N4401
Q2	2N4036
Q3	2N2102
Q4	D40D1
Q5	D41D1

Figure A.14; Stage 2 Output Current Limiter.

Capacitors:

Table A.1 (cont'd.)

C1	0.047 μF
C2	0.033 μF
C3,C4	0.47 μF
Diodes:	
D1-D7	1N4148
IC Chips:	
CA324E	
Resistors:	
R1	56.0 $k\Omega$
R2,R5	100.0 $K\Omega$
R3	220.0 Ω
R4	10.0 $k\Omega$ trimpot
R6	27.0 $k\Omega$
Transformers:	
CT-A,B,C	Np = 1 turn, #12 magnet wire Ns = 200 turns, #28 magnet wire 2616 Ferrite pot core

Figure A.15; Stage 2 Voltage Limiter and Error Amplifier.

Capacitors:	
C1	0.12 μF
C2	0.033 μF
Diodes:	
D1-D6	1N4148
IC Chips:	
CA324E	
LM339	
Resistors:	
R1	24.0 $k\Omega$
R2,R5,R8,R9	100.0 $k\Omega$
R3	220.0 Ω
R4,R7	10.0 $k\Omega$ trimpot
R6	27.0 $k\Omega$
R10	1.0 $M\Omega$
R11-R13,R15	10.0 $k\Omega$
R14	56.0 $k\Omega$
R16	12.0 $k\Omega$
Transformer:	
PT-A	Np = 200 turns, #28 magnet wire Ns = 5 turns, #28 magnet wire 3622 Ferrite pot core
Transistor:	
Q1	2N4403

Appendix B

THREE PHASE CASCADED SCHWARZ CONVERTER SCHEMATICS

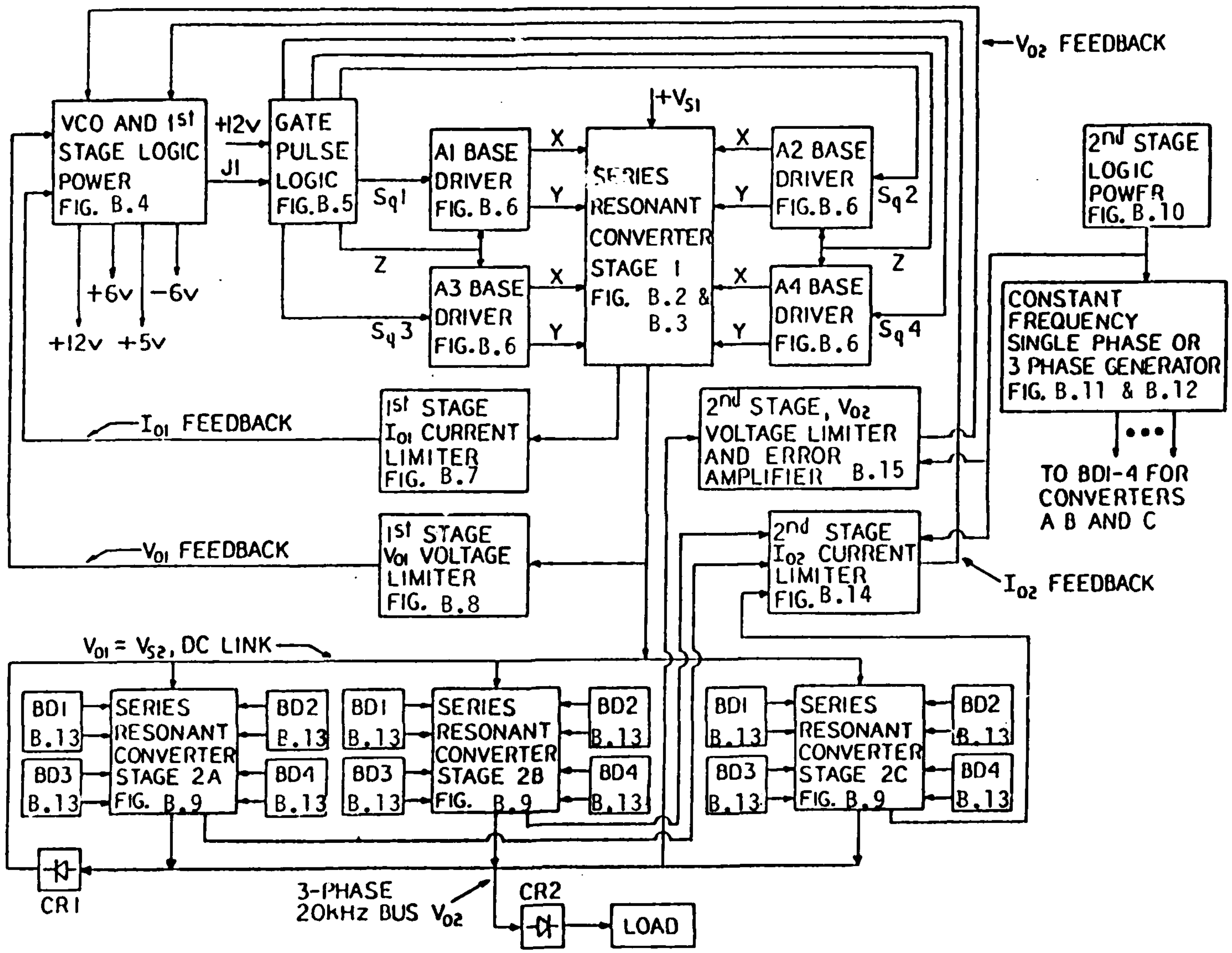

Figure B.1: Three Phase Cascaded Schwarz Converter Block Diagram.

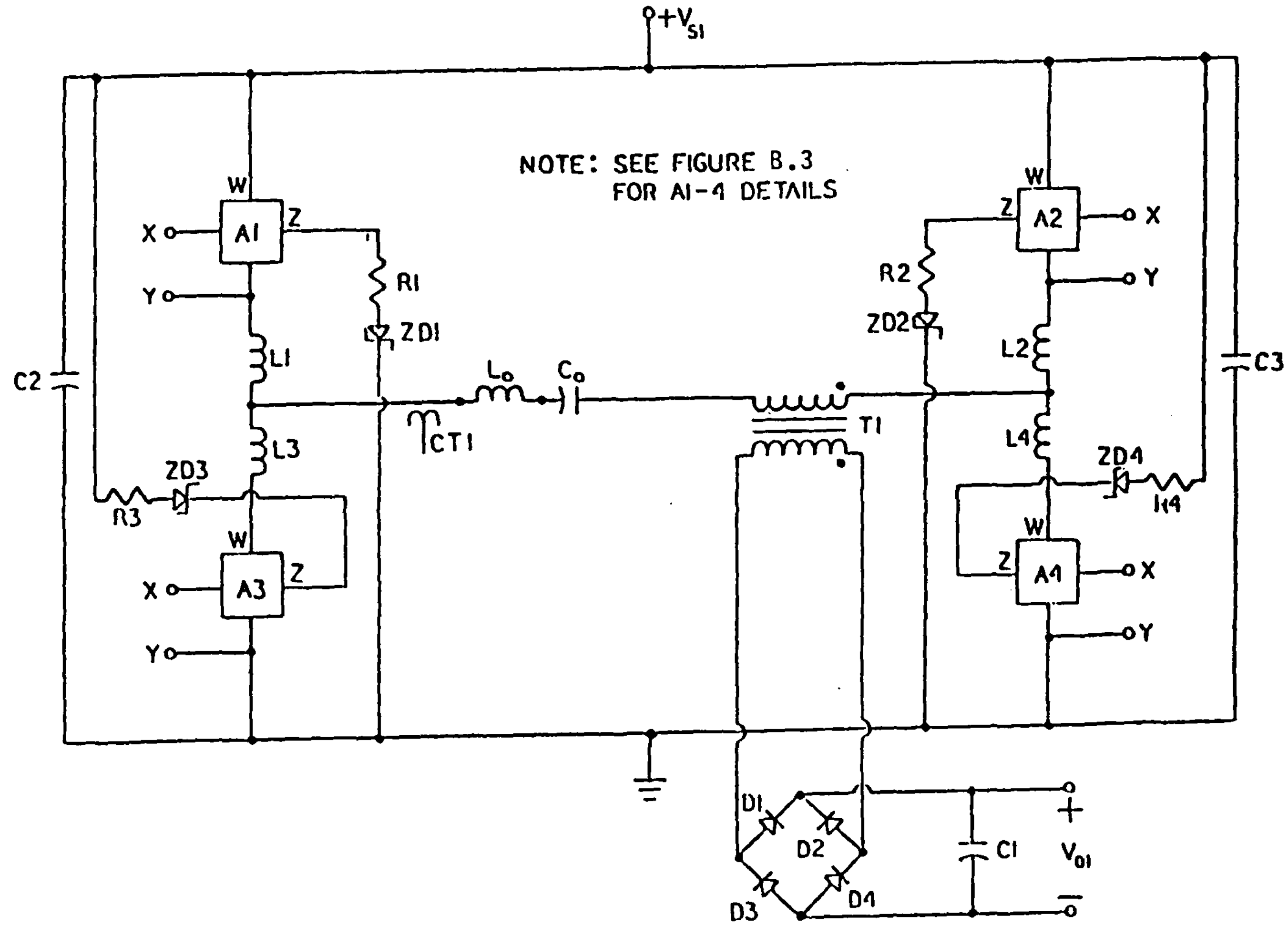

Figure B.2: Stage 1 Variable Frequency Series Resonant Converter.

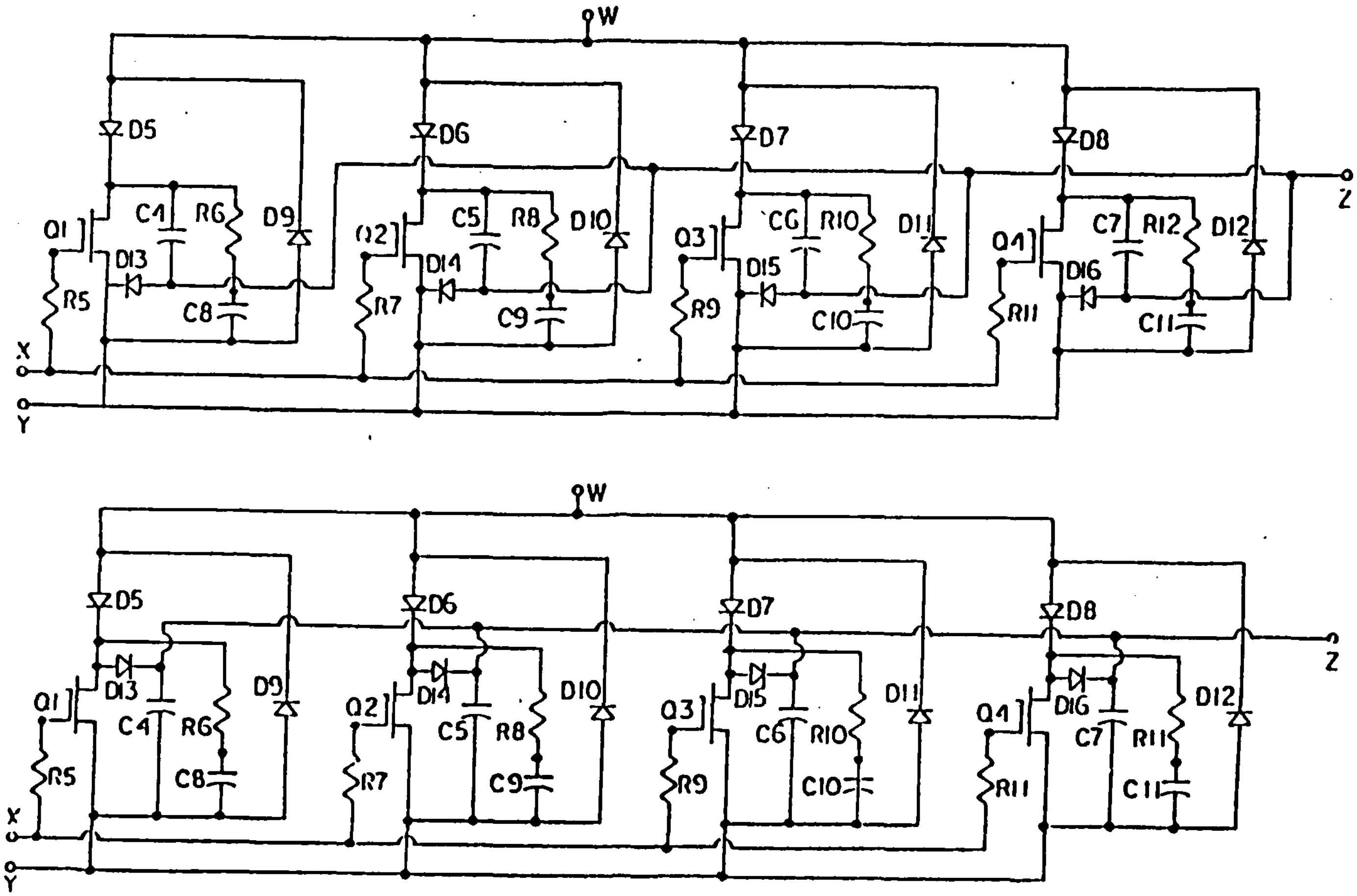

Figure B.3: Top - Blocks A1 and A2. Bottom - Blocks A3 and A4.

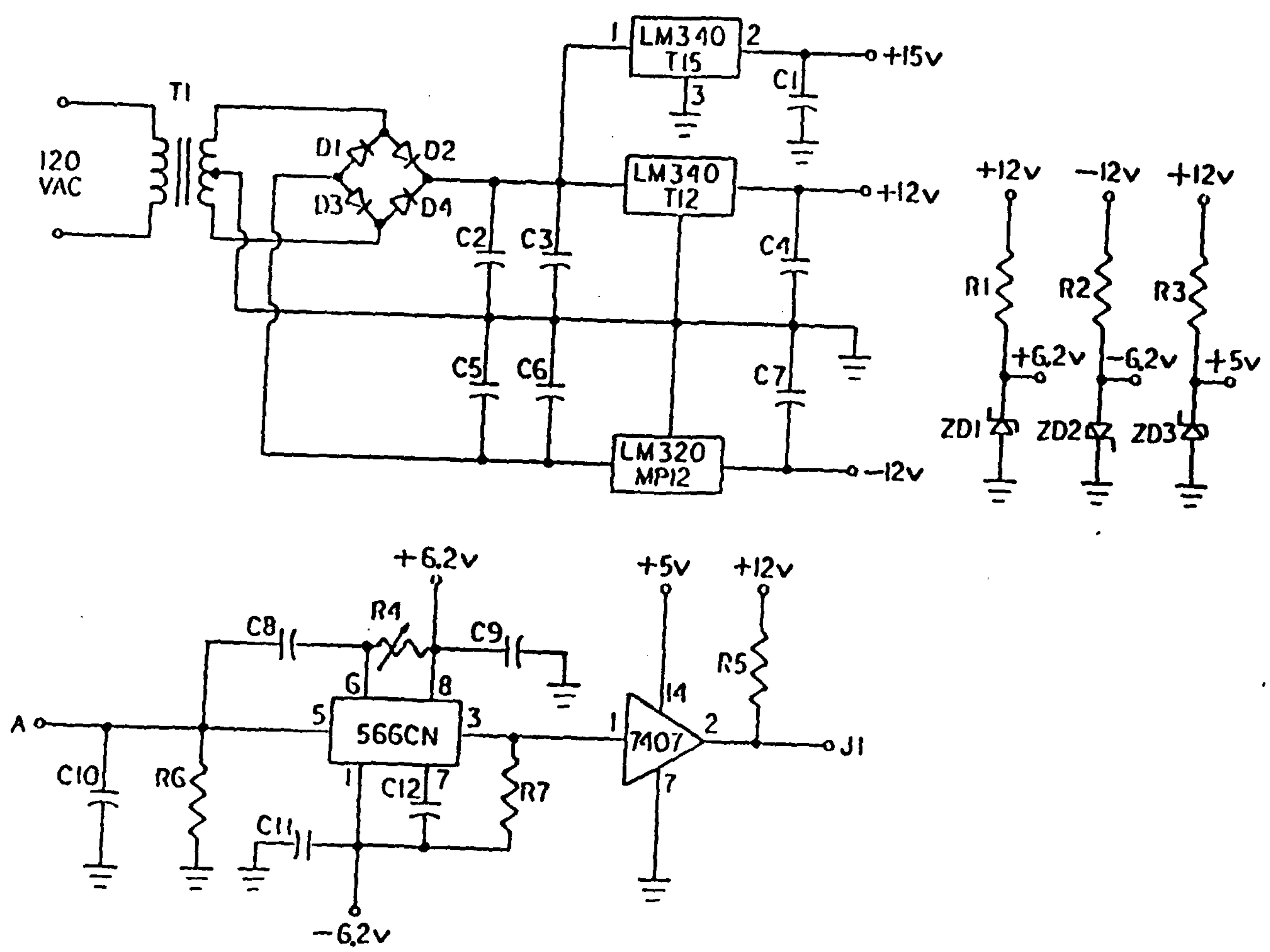

Figure B.4: VCO and Stage 1 Logic Power Supply.

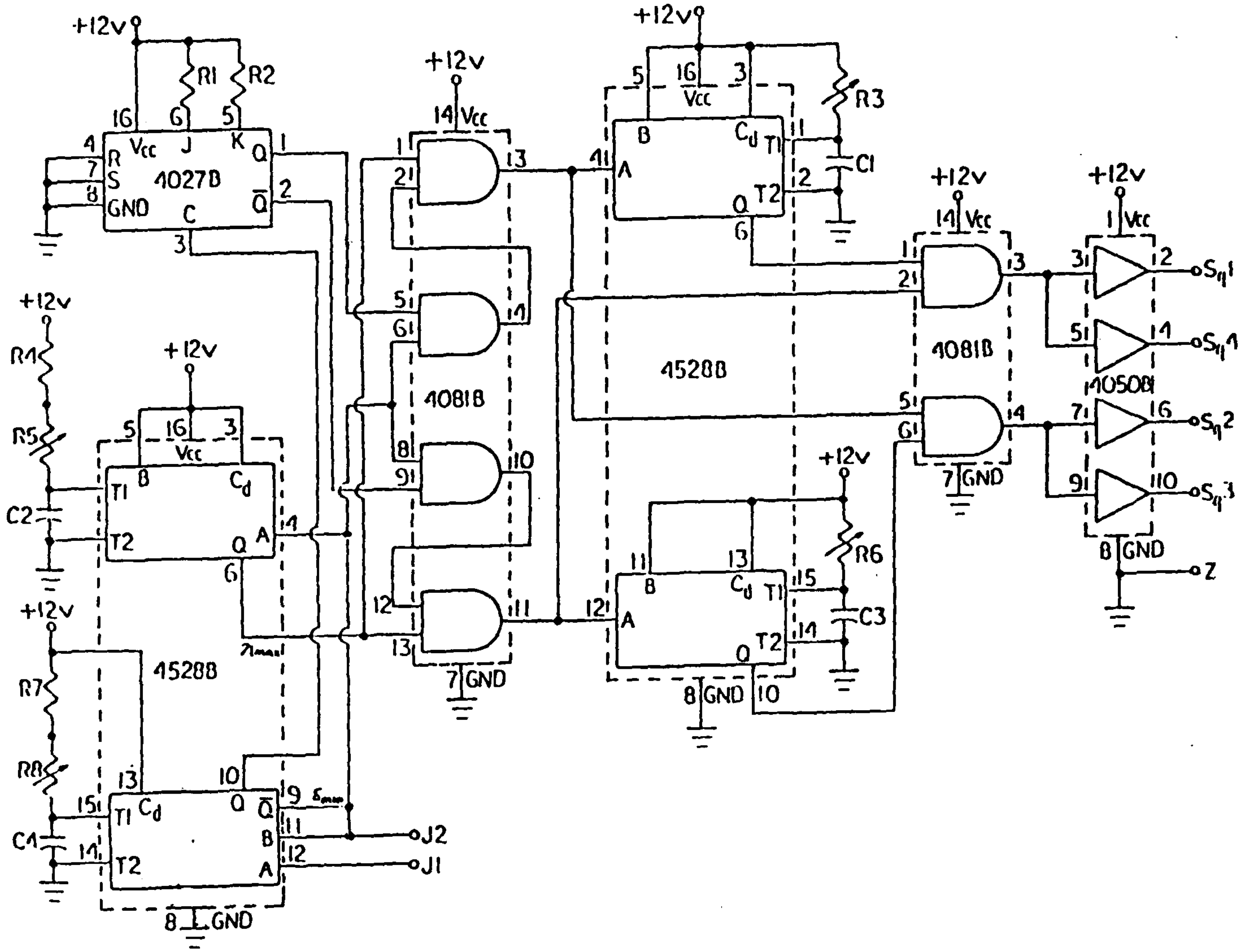

Figure B.5: Stage 1 Gate Pulse Logic.

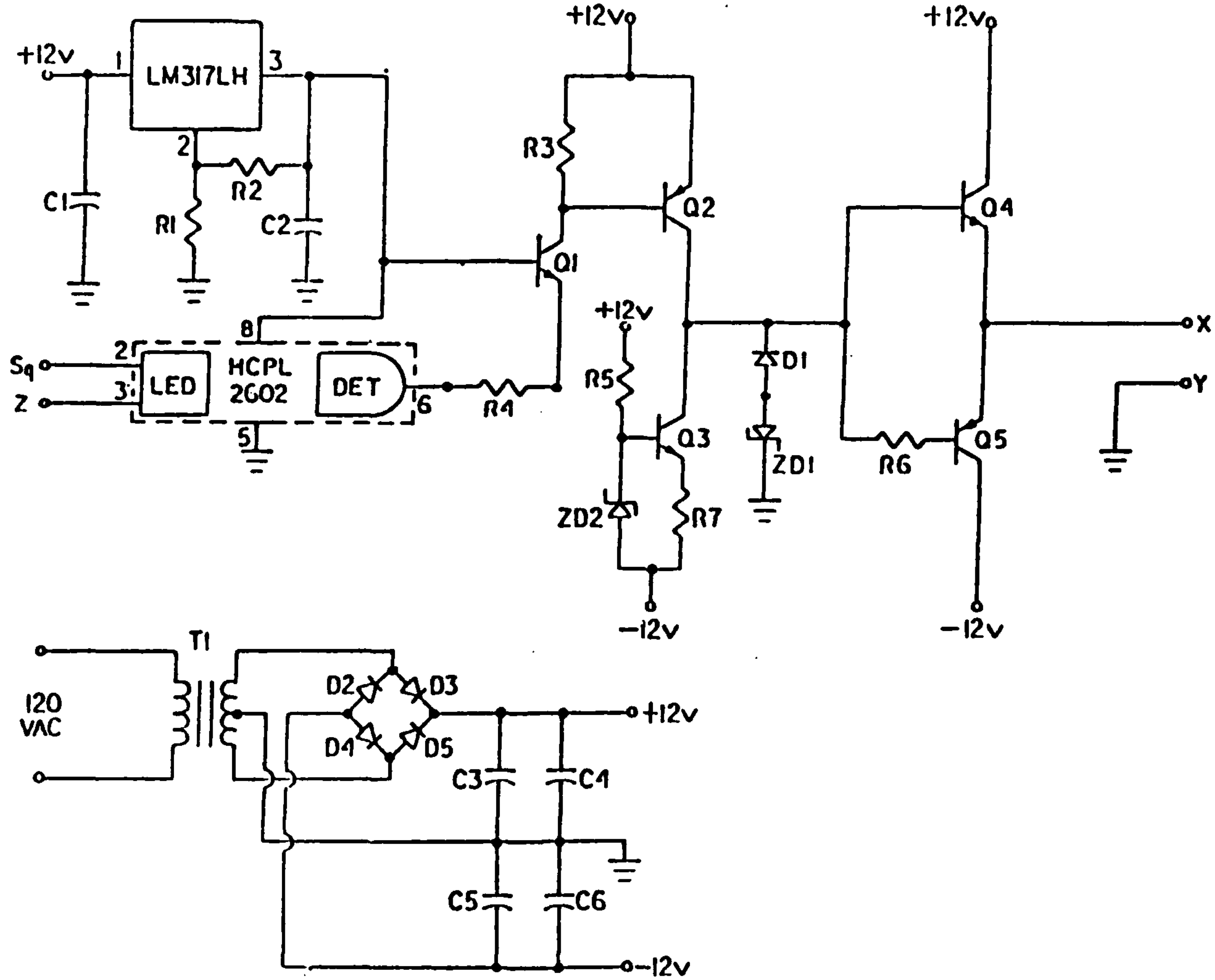

Figure B.6: Stage 1 MOSFET Transistor Base Drive.

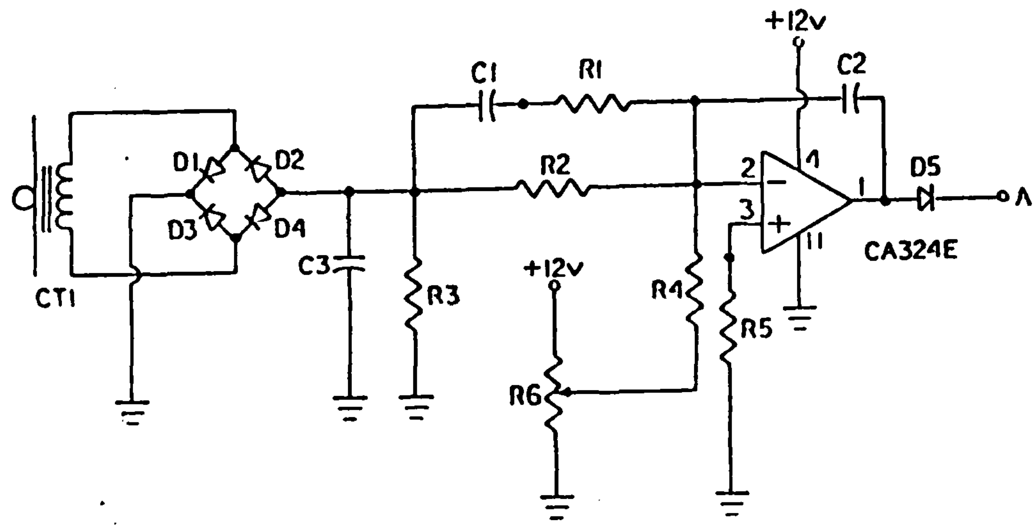

Figure B.7: Stage 1 Output Current Limiter.

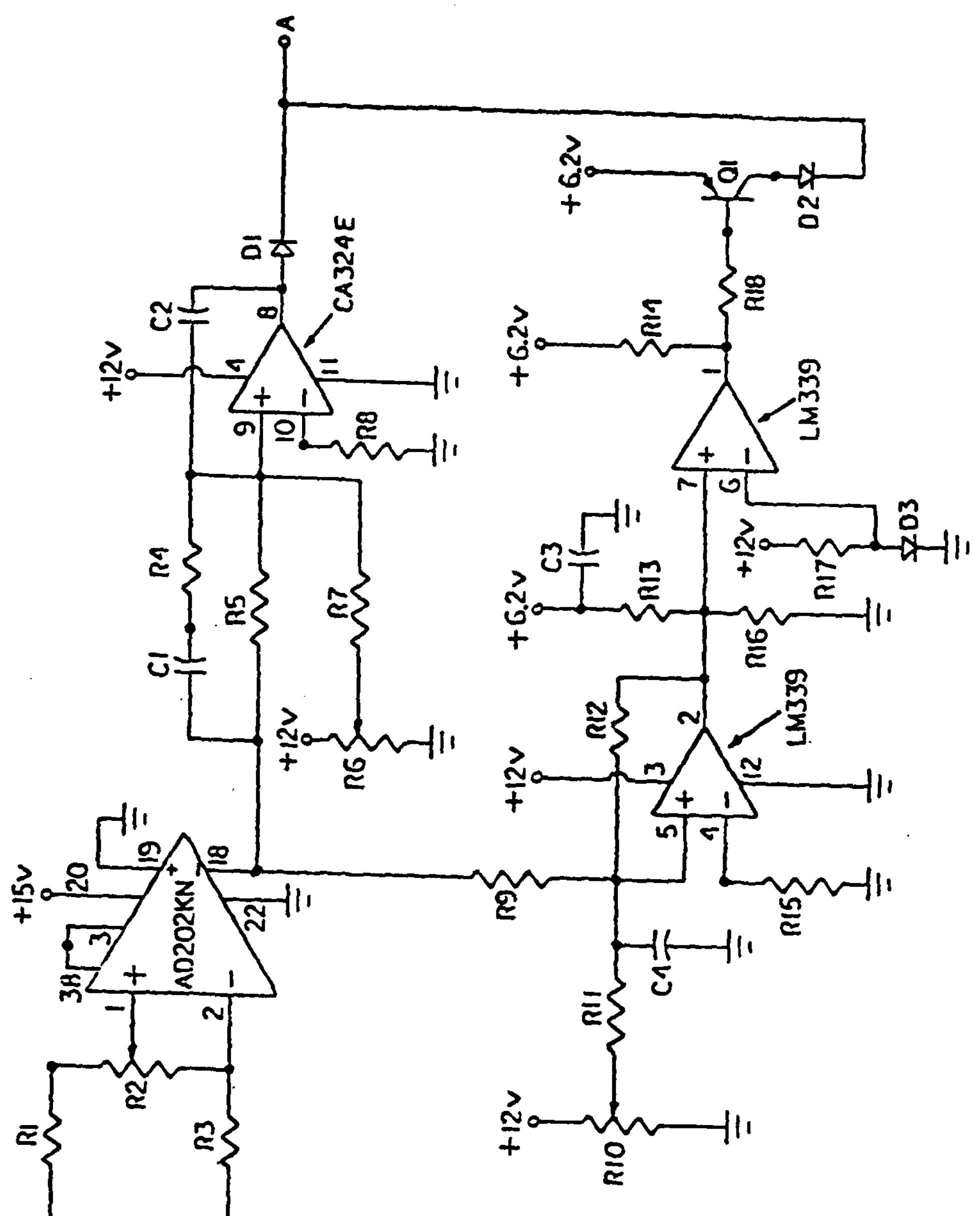

Figure B.8: Stage 1 Voltage Limiter.

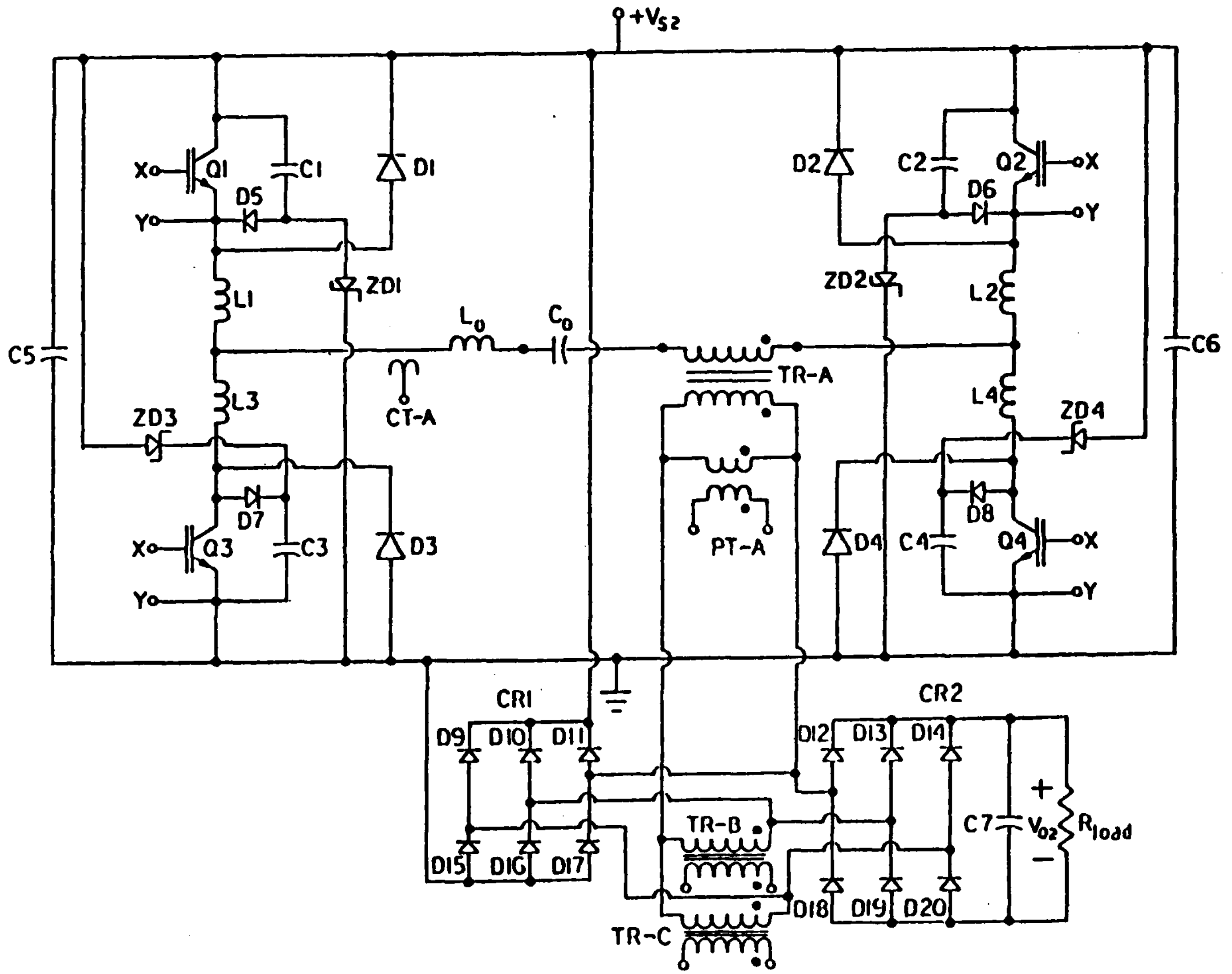

Figure B.9: Stage 2 - Phase A Series Resonant Inverter, Connections to Phases B and C, Typical Load Rectifier CR2 and Recycline Rectifier CR1.

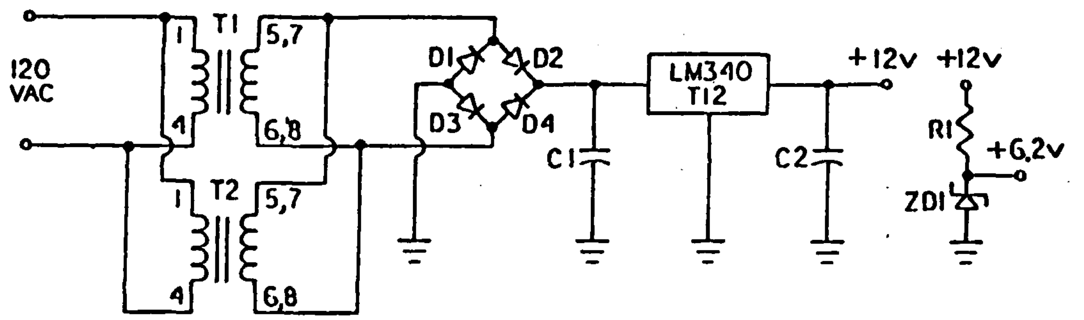

Figure B.10: Stage 2 Logic Power Supply.

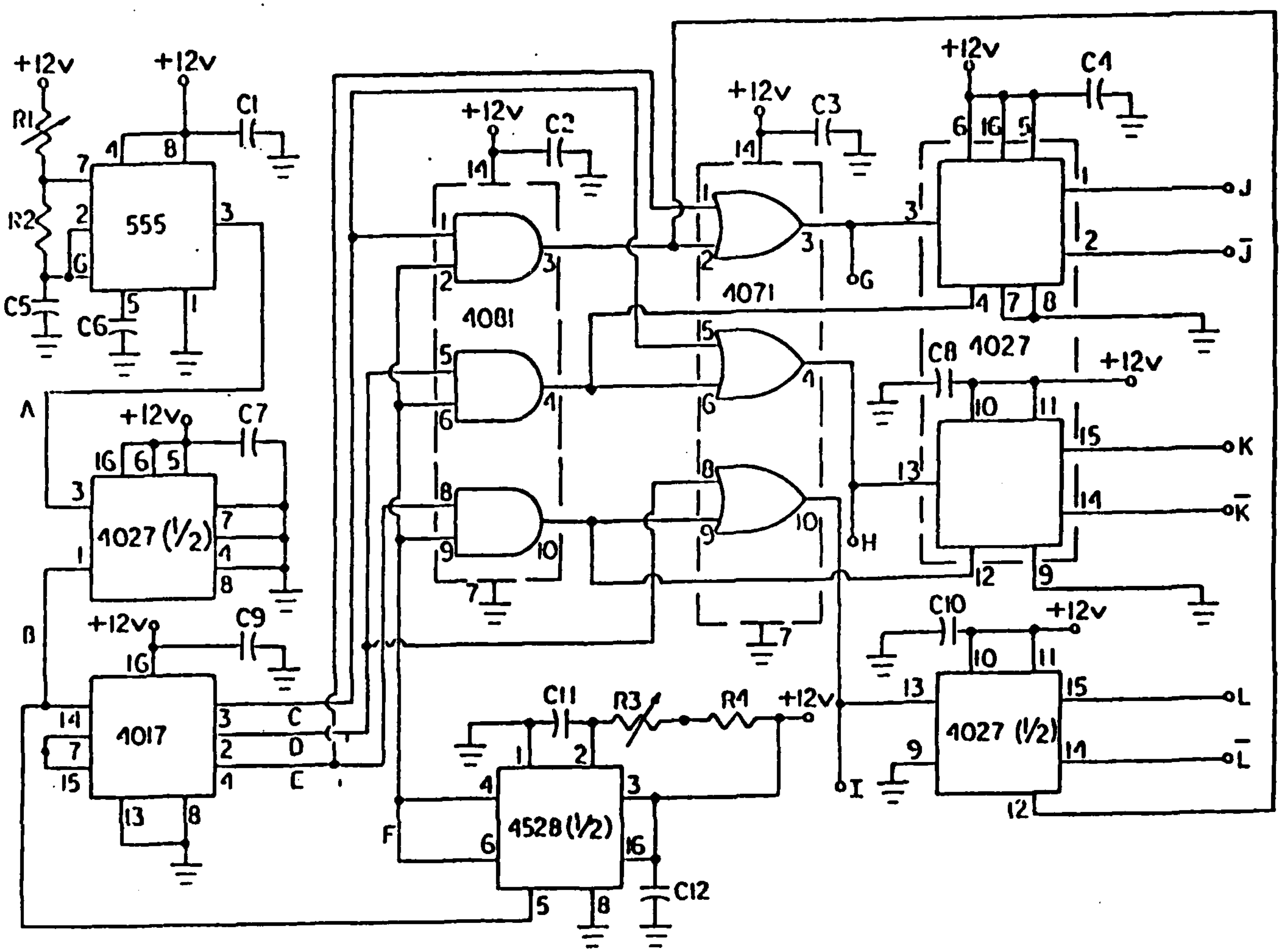

Figure B.11: Stage 2 Constant Frequency Single Phase or Three Phase Generator.

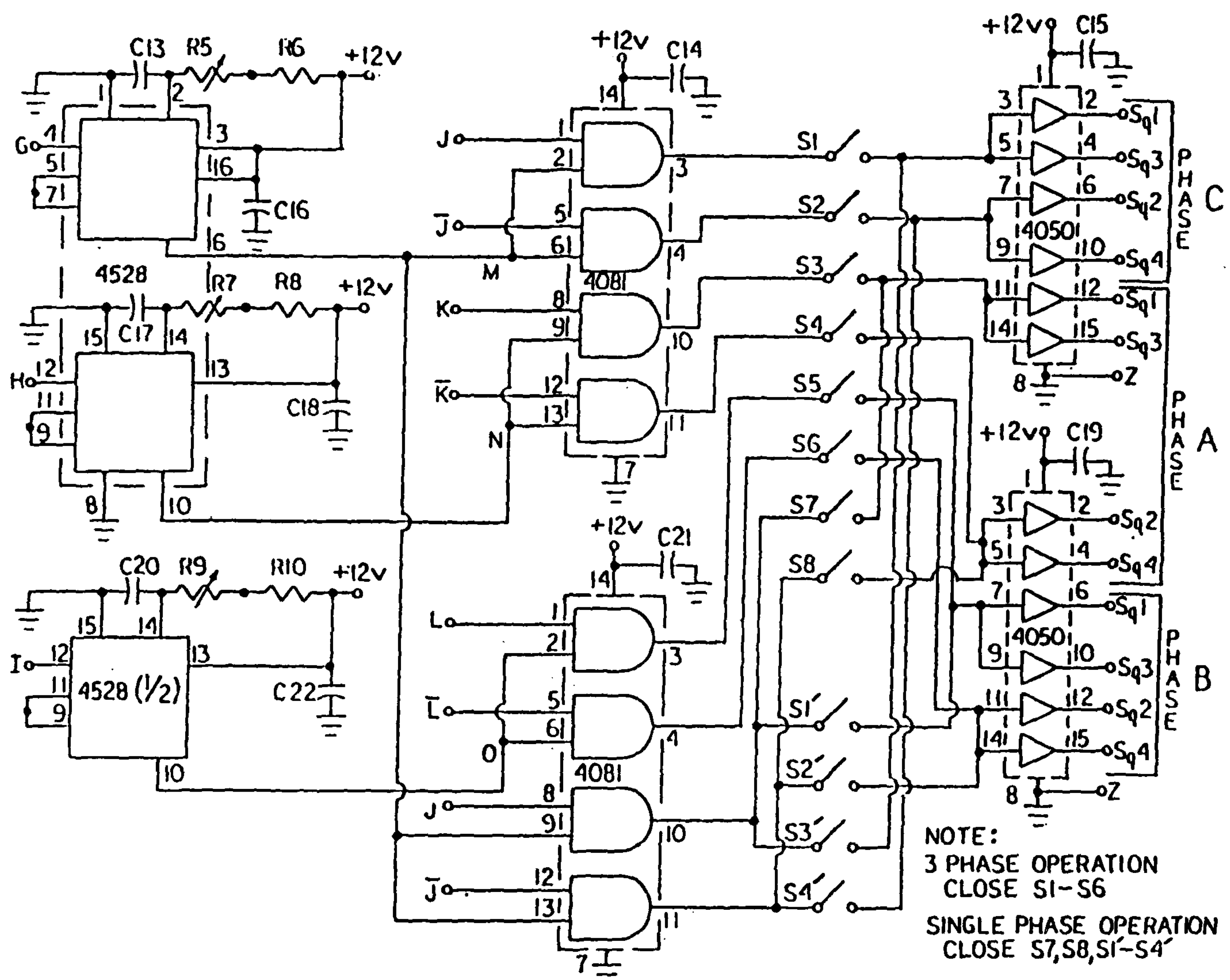

Figure B.12: Stage 2 Constant Frequency Single Phase or Three Phase Generator (continued).

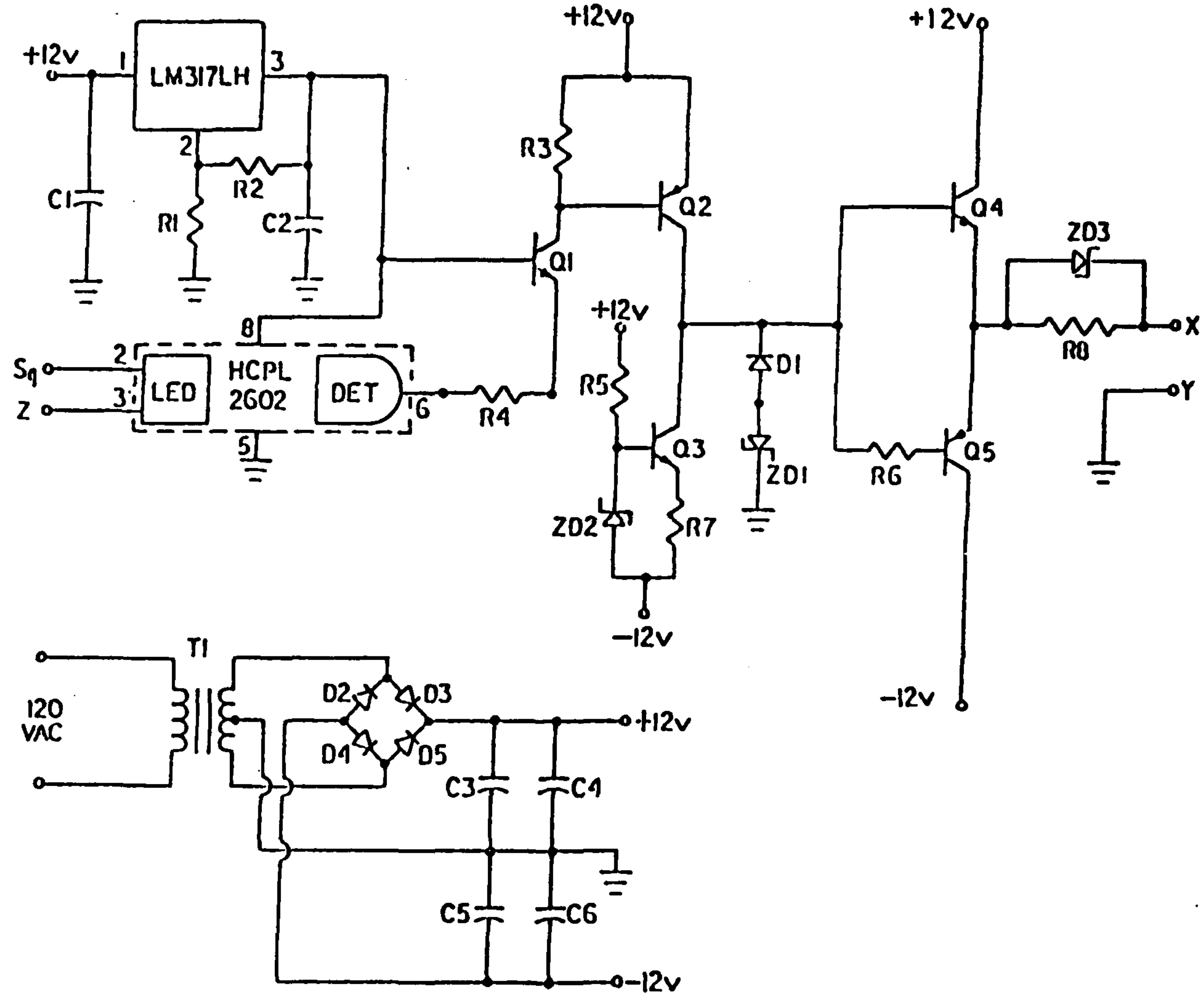

Figure B.13: Stage 2 Phases A, B and C Insulated Gate Transistor Base Drive.

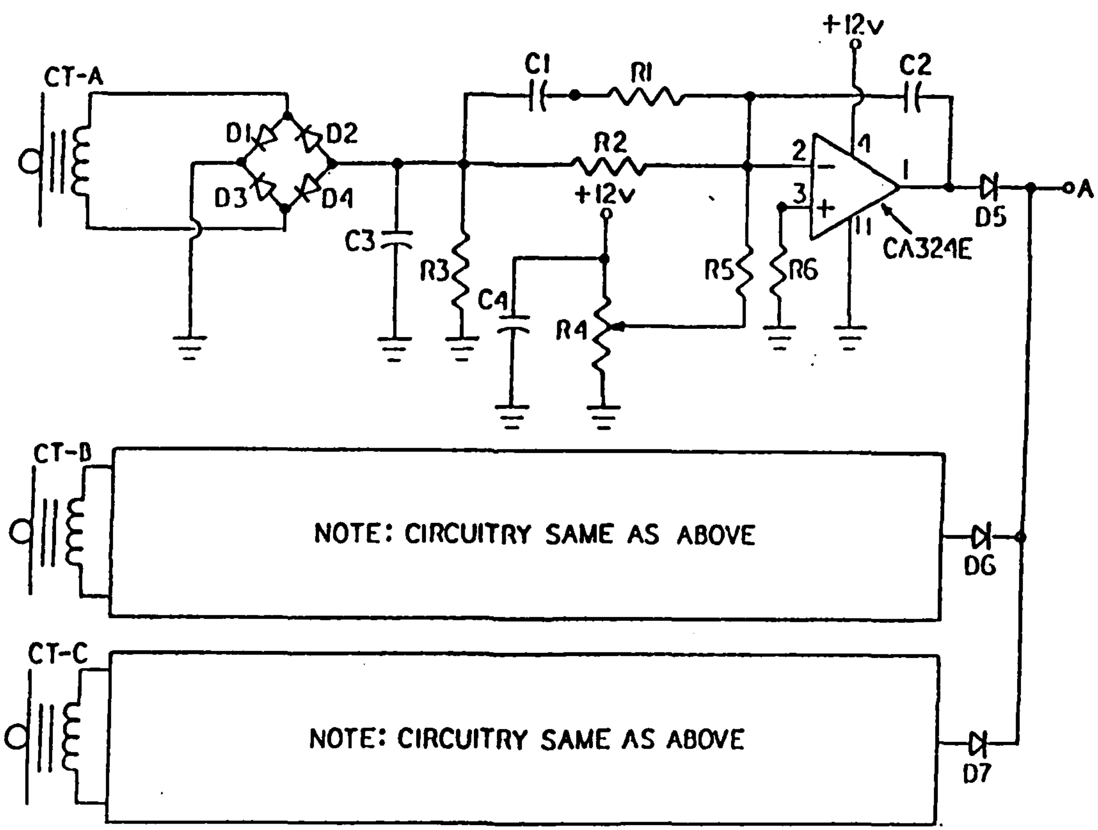

Figure B.14: Stage 2 Output Current Limiter.

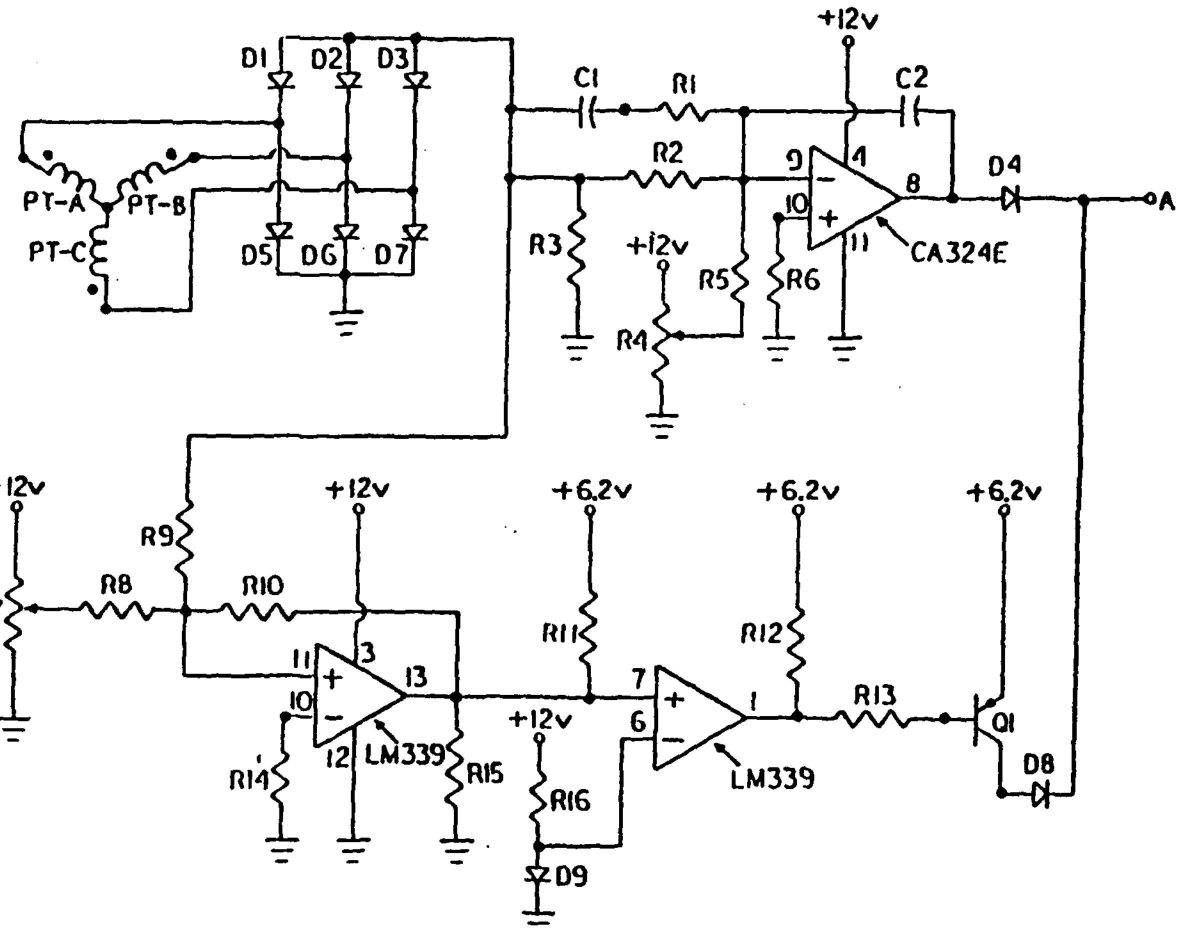

Figure B.15: Stage 2 Voltage Limiter and Error Amplifier.

Table B.1: 2500-watt Three Phase Cascaded Schwarz Converter Parts List

Figure B.2; Stage 1 Variable Frequency Series Resonant Converter.

Capacitors:	
C_o	1.24 μF
C1	0.270 μF
C2,C3	0.20 μF (polypropolene)
Diodes:	
D1-D4	MR1386
Zener Diodes:	
ZD1-ZD4	1N2819A
Inductors:	
L_o	45.0 μH
L1-L4	4.0 μH
Resistors:	
R1-R4	2.2 Ω 3 Watt
Transformers:	
T1	Np = 32 turns, 16 strands 50/36 litz Ns = 164 turns, 3 strands 50/36 litz Ferrite core
CT1	Np = 1 turn, 8 strands 36/50 litz Ns = 210 turns, #24 magnet wire 4229 Ferrite pot core

Figure B.3; Top - Blocks A1 and A2. Bottom - Blocks A3 and A4.

Capacitors:	
C4-C7	0.033 μF
C8-C11	0.0022 μF
Diodes:	
D5-D8	1N5829
D9-D12	1N3911
D13-D16	MR824
Resistors:	
R5,R7,R9,R11	27.0 Ω 1/2 Watt
R6,R8,R10,R12	100.0 Ω 5.0 Watt
Transistors (MOSFETS):	
Q1-Q4	MTM404N20

Table B.1 (cont'd.)

Figure B.3; VCO and Stage 1 Logic Power Supply.

Capacitors:	
C1,C4,C7,C10	0.1 μF
C2,C5	100.0 μF
C3,C6	224.0 μF
C8	0.001 μF
C9, C11	0.47 μF
C12	0.01 μF
Diodes:	
D1-D4	1N4005
IC Chips:	
LM320MP12	
LM340T12	
LM340T15	
566CN	
7407	
Resistors:	
R1-R3	270.0 Ω
R4	5.0 kΩ trimpot
R5	10.0 kΩ
R6	100.0 kΩ
R7	4.7 kΩ
Transformers:	
T1	Signal Transformer ST-3-36

Figure B.5; Gate Pulse Logic.

Capacitors:	
C1,C2	200.0 pF
C3,C4	0.047 μF
IC Chips:	
CD4027B	
CD4050B	
MC1 4528B	
SC14801A	
Resistors:	
R1,R2	1.0 kΩ
R3	47.0 kΩ
R4	100.0 kΩ trimpot
R5	10.0 kΩ
R6	10.0 kΩ trimpot
R7,R8	100.0 kΩ

Figure B.6; Stage 1 MOSFET Transistor Base Drive.

Capacitors:	
C1,C2	0.1 μF

Table B.1 (cont'd.)

C3-C6	2200.0 μF
Diodes:	
D1	1N4935
D2-D5	1N4005
Zener Diodes:	
ZD1	1N4733
ZD2	1N4731
IC Chips:	
LM317LH	
HP2602	
Resistors:	
R1	1.2 kΩ
R2	330.0 Ω
R3	470.0 Ω
R4	830.0 Ω
R5	1.0 kΩ
R6	82.0 Ω
R7	47.0 Ω
R8	20.0 Ω 1/2 Watt
Transformer:	
T1	Signal Transformer ST-5-16
Transistors:	
Q1	2N4401
Q2	2N4036
Q3	2N2102
Q4	D40D1
Q5	D41D1

Figure B.7; Stage 1 Output Current Limiter.

Capacitors:	
C1	0.047 μF
C2	0.033 μF
C3	0.47 μF
Diodes:	
D1-D5	1N4148
IC Chips:	
CA324E	
Resistors:	
R1	56.0 kΩ
R2,R4	100 kΩ
R3	220.0 Ω
R5	27.0 kΩ
R6	10.0 kΩ trimpot

Table B.1 (cont'd.)

Transformer:	
CT1	Np = 1 turn, 8 strands 36/50 litz Ns = 240 turns, #24 magnet wire 4229 Ferrite core

Figure B.8; Stage 1 Voltage Limiter.

Capacitors:	
C1	0.047 μF
C2	0.033 μF
C3	330.0 pF
Diodes:	
D1-D3	1N4148
Resistors:	
R1,R3	560.0 $k\Omega$
R2	20.0 $k\Omega$
R4,R8,R15	56.0 $k\Omega$
R5,R7,R9,R11	100.0 $k\Omega$
R6,R10	10.0 $k\Omega$ trimpot
R12	1.0 $M\Omega$
R13,R14,R16,R18	10.0 $k\Omega$
R17	20.0 $k\Omega$
Transistor:	
Q1	2N4403

Figure B.10; Stage 2 - Phase A Series Resonant Inverter, Connections to Phases B and C, Typical Load Rectifier CR-2 and Recycling Rectifier CR-1.

Capacitors:	
C_o	0.0656 μF
C1-C4	0.047 μF
C5,C6	10.0 μF
C7	270.0 μF
Diodes:	
D1-D4	MUR840
D5-D8	MR916
D9-D20	MR1386
Zener Diodes:	
ZD1-ZD4	1N3028B
Inductors:	
L_o	1.05 mH
L1-L4	11.3 μH
Transformers:	
CT-A	Np = 1 turn, #12 magnet wire Ns = 200 turns, #28 magnet wire

Table B.1 (cont'd.)

	2616 Ferrite pot core
PT-A	Np - 200 turns, #28 magnet wire Ns - 5 turns, #28 magnet wire 3622 Ferrite pot core
TR-A,B,C	Np-Ns - 76 turns, 1 strand 36/50 litz (38 turns/spool) IG69.85 Ferrite E-core
Transistors:	
Q1-Q4	IGT4D10

Figure B.10: Stage 2 Logic Power Supply.

Capacitors:	
C1	1000.0 μF
C2	0.1 μF
Diodes:	
D1-D4	1N4007
Zener Diodes:	
ZD1	1N5234
IC Chips:	
LM340T12	
Resistors:	
R1	270.0 Ω
Transformers:	
T1,T2	Signal Transformer ST-3-36

Figure B.11 and B.12; Stage 2 Constant Frequency Single Phase or Three Phase Generator.

Capacitors:	
C1-C4,C7-C10,C14-C16 C18,C19,C21,C22	0.1 μF
C5,C13,C17-C20	0.0033 μF
C6	0.01 μF
C11	10.0 pF
IC Chips:	
NE555	
4017	
4027	
4050	
4071	
4081	
4528	

Table B.1 (cont'd.)

Resistors:

R1	1.0 kΩ trimpot
R2	1.6 kΩ
R3,R5,R7,R9	10.0 kΩ trimpot
R4	15.0 kΩ
R6,R8,R10	10.0 kΩ

Switches:
8 pin Dip Switch
4 pin Dip Switch

Figure B.13: Stage 2 Phases A, B and C Insulated Gate Transistor Base Drive.

Capacitors:

C1,C2	0.1 μF
C3-C6	2200.0 μF

Diodes:

D1	1N4935
D2-D5	1N4005

Zener Diodes:

ZD1	1N4733
ZD2	1N4731
ZD3	1N4734A

IC Chips:
LM317LH
HP2602

Resistors:

R1	1.2 kΩ
R2	330.0 Ω
R3	470.0 Ω
R4	830.0 Ω
R5	1.0 kΩ
R6	47.0 Ω
R7	82.0 Ω
R8	100.0 Ω 1/2 Watt

Transformer:

T1	Signal Transformer ST-5-16

Transistors:

Q1	2N4401
Q2	2N4036
Q3	2N2102
Q4	D40D1
Q5	D41D1

Figure B.14; Stage 2 Output Current Limiter.

Capacitors:

Table B.1 (cont'd.)

C1	0.047 μF
C2	0.033 μF
C3,C4	0.47 μF
Diodes:	
D1-D7	1N4148
IC Chips:	
CA324E	
Resistors:	
R1	56.0 kΩ
R2,R5	100.0 KΩ
R3	220.0 Ω
R4	10.0 kΩ trimpot
R6	27.0 kΩ
Transformers:	
CT-A,B,C	Np = 1 turn, #12 magnet wire Ns = 200 turns, #28 magnet wire 2616 Ferrite pot core

Figure B.15: Stage 2 Voltage Limiter and Error Amplifier.

Capacitors:	
C1	0.12 μF
C2	0.033 μF
Diodes:	
D1-D6	1N4148
IC Chips:	
CA324E	
LM339	
Resistors:	
R1	24.0 kΩ
R2,R5,R8,R9	100.0 kΩ
R3	220.0 Ω
R4,R7	10.0 kΩ trimpot
R6	27.0 kΩ
R10	1.0 MΩ
R11-R13,R15	10.0 kΩ
R14	56.0 kΩ
R16	12.0 kΩ
Transformer:	
PT-A	Np = 200 turns, #28 magnet wire Ns = 5 turns, #28 magnet wire 3622 Ferrite pot core
Transistor:	
Q1	2N4403

Appendix C

SINGLE PHASE CASCADED SCHWARZ CONVERTER DESIGN PROGRAM

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
C     SINGLE PHASE CASCADED SCHWARZ CONVERTER DESIGN PROGRAM
C
C     Author: Russell E. Shetler, Jr.
C
C     Description:
C
C        This program determines the currents, voltages, transistor
C        commutation times and resonant component values for the design
C        of the single phase cascaded Schwarz converter.  The user must
C        supply the following data at execution time:
C
C           DC input voltage to stage one,
C           DC output voltage of stage two,
C           Average DC output current of stage two,
C           First stage efficiency,
C           Second stage efficiency,
C           First stage transformer turns ratio,
C           Second stage transformer turns ratio,
C           The ratio of the characteristic impedance of stage one to
C           the characteristic impedance of stage two,
C           The resonant frequency of stage one,
C           The maximum operating frequency of stage one,
C           The resonant frequency of stage two,
C           The fixed operating frequency of stage two.
C
C        The program will then generate the values for the currents,
C        voltages, commutation times and resonant components.
C
C     Algorithm:
C
C        This program uses a IMSL library subroutine "ZSPOW" to solve the
C        nonlinear equations which describe the single phase cascaded
C        Schwarz converter.
C
C     Input Format:
C
C        The required data is supplied at execution time.  The format for
C        the required data is specified by a write statament at execution
C        time.
C
C     Output Format:
C
C        The program output consists of a brief explanatory header, a
C        statement of the parameters being calculated and the values of
C        the given parameters.
C
C     Variable Dictionary:
C
C        A = Variable to determine if more data is to be entered.
C        ALPHA1 = Delay angle of stage one (an unknown).
C        ALPHA2 = Delay angle of stage two (an unknown).
```

```
C         AL1MIN = The minimum acceptable value of ALPHA1.
C         AL2MIN = The minimum acceptable value of ALPHA2.
C         C1 = The resonant capacitor of stage one.
C         C2 = The resonant capacitor of stage two.
C         FCN = A subroutine which contains the nonlinear equations to be
C              solved.
C         FO1 = The resonant frequency of stage one (in Hertz).
C         FO2 = The resonant frequency of stage two (in Hertz).
C         FS1MAX = The maximum operating frequency of stage one (in
C                 Hertz).
C         FS2 = The fixed operating frequency of stage two (in Hertz).
C         GAMMA1 = The total conduction angle of stage one.
C         GAMMA2 = The total conduction angle of stage two.
C         IA1 = The average output current of stage one.
C         IA1NR = The normalized average output current of stage one
C                reflected to its transformer secondary.
C         IA1R = The average output current of stage one reflected to
C               its transformer secondary.
C         IA2 = The average output current of stage two.
C         IA2R = The average output current of stage two reflected to
C               its transformer primary.
C         IA2N = The normalized average output current of stage two.
C         IB1R = The base current of stage one reflected to its
C               transformer secondary.
C         IB2R = The base current of stage two reflected to its
C               transformer primary.
C         IDA1 = The average diode current of stage one.
C         IDA1NR = The normalized average diode current of stage one
C                 reflected to its transformer secondary.
C         IDA1R = The average diode current of stage one reflected to
C                its transformer secondary.
C         IDA2 = The average diode current of stage two.
C         IDA2N = The normalized average diode current of stage two.
C         IER = Error parameter.
C         IPK1 = The peak current of stage one.
C         IPK1NR = The normalized peak current of stage one reflected to
C                 its transformer secondary.
C         IPK1R = The peak current of stage one reflected to its
C                transformer secondary.
C         IPK2 = The peak current of stage two.
C         IPK2N = The normalized peak current of stage two.
C         IQA1 = The average transistor current of stage one.
C         IQA1NR = The normalized average transistor current of stage one
C                 reflected to its transformer secondary.
C         IQA1R = The average transistor current of stage one reflected
C                to its transformer secondary.
C         IQA2 = The average transistor current of stage two.
C         IQA2N = The normalized average transistor current of stage two.
C         IRMS1 = The RMS current of stage one.
C         IRM1NR = The normalized RMS current of stage one reflected to
C                 its transformer secondary.
C         IRMS1R = The RMS current of stage one reflected to its
C                 transformer secondary.
C         IRMS2 = The RMS current of stage two.
```

```
C          IRMS2N = The normalized RMS current of stage two.
C          ITMAX = The maximum number of iterations.
C          IO1NR = Normalized average current of stage one at time t=0
C                 reflected to its transformer secondary.
C          IO2N = Normalized average current of stage two at time t=0.
C          K12 = The ratio of the characteristic impedance of stage one to
C                the characteristic impedance of stage two.
C          K12R = The value of K12 reflected to the secondary of the stage
C                 one transformer.
C          L1 = The resonant inductor of stage one.
C          L2 = The resonant inductor of stage two.
C          N = The number of equations to be solved and the number of
C              unknowns.
C          NSIG = The number of digits of accuracy desired in the computed
C                 roots.
C          NU1 = The efficiency of stage one.
C          NU2 = The efficiency of stage two.
C          N1 = The stage one transformer turns ratio (N1/N2).
C          N2 = The stage two transfomer turns ratio (N1/N2).
C          PAR(5) = A parameter set used to pass information between programs.
C          PI = A constant equal to 3.1415927.
C          Q1R = The ratio of the output voltage to the input voltage of stage
C                one (an unknown).
C          Q2R = The ratio of the output voltage to the input voltage of stage
C                two.
C          Q12R = The ratio of the ouput voltage of stage two to the input
C                 voltage of stage one.
C          T1Q = The commutation time of the stage one transistors.
C          T2Q = The commutation time of the stage two transistors.
C          VB1R = The base voltage of stage one reflected to its transformer
C                 secondary.
C          VB2R = The base voltage of stage two reflected to its transformer
C                 primary.
C          VCPK1 = The peak capacitor voltage of stage one.
C          VCP1NR = The normalized peak capacitor voltage of stage one
C                   reflected to its transformer secondary.
C          VCPK1R = The peak capacitor voltage of stage one reflected to
C                   the transformer secondary.
C          VCPK2 = The peak capacitor voltage of stage two.
C          VCPK2N = The normalized peak capacitor voltage of stage two.
C          VCO1NR = The normalized stage one capacitor voltage at time t=0
C                   reflected to its transformer secondary.
C          VCO2N = The normalized stage two capacitor voltage at time t=0.
C          VC11NR = The normalized stage one capacitor voltage at time t=1
C                   reflected to its transformer secondary.
C          VC12N = The normalized stage two capacitor voltage at time t=1.
C          VO1R = The reflected link voltage between stage one and two.
C          VO2 = The output voltage of stage two.
C          VO2EFF = The output voltage of stage two taking into account
C                   the efficeincy of stage two.
C          VO2R = The output voltage of stage two reflected to the
C                 primary of its transformer.
C          VS1 = The input voltage to stage one.
C          VS1EFF = The input voltage to stage one taking into account
```

```
C              the efficeincy of stage one.
C         VS1R = The input voltage to stage one reflected to its transformer
C                secondary.
C         WK(36) = A block of memory used by ZSPOW for calculations.
C         WO1 = The radian resonant frequency of stage one.
C         WO2 = The radian resonant frequency of stage two.
C         X(3) = A vector of the unknowns: On input it contains the initial
C                guess of the roots and on output it contains the best
C                approximation to the root.
C         ZO1 = The characteristic impedance of stage one.
C         ZO1R = The characteristic impedance of stage one reflected to
C                its transformer secondary.
C         ZO2 = The characteristic impedance of stage two.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C---------------------------------------------------------------------
C     DECLARE VARIABLES TO BE USED
C---------------------------------------------------------------------
      INTEGER N,NSIG,ITMAX,IER,A
C
      REAL ALPHA1,ALPHA2,AL1MIN,AL2MIN,BETA1,BETA2,C1,C2,FO1,FO2
      REAL FS1MAX,FS2,GAMMA1,GAMMA2,IA1,IA1NR,IA1R,IA2,IA2N,IA2R,IB1R
      REAL IB2R,IDA1,IDA1NR,IDA1R,IDA2,IDA2N,IPK1,IPK1NR,IPK1R,IPK2
      REAL IPK2N,IQA1,IQA1NR,IQA1R,IQA2,IQA2N,IRMS1,IRM1NR,IRMS1R
      REAL IRMS2,IRMS2N,IO1NR,IO2N,K12,K12R,L1,L2,NU1,NU2,N1,N2
      REAL PAR(5),PI,Q1R,Q2R,Q12R,T1Q,T2Q,VCPK1,VCP1NR,VCPK1R,VCPK2
      REAL VCPK2N,VCO1NR,VCO2N,VC11NR,VC12N,WK(36),WO1,WO2,X(3),VB1R
      REAL VB2R,VO2,VO2EFF,VO2R,VS1,VS1EFF,VS1R,ZO1,ZO1R,ZO2
C---------------------------------------------------------------------
C     DECLARE EXTERNAL SUBROUTINES
C---------------------------------------------------------------------
      EXTERNAL FCN
C---------------------------------------------------------------------
C     PRINT OUTPUT HEADER
C---------------------------------------------------------------------
      PRINT*
      PRINT*
      PRINT*
      PRINT*,'This program determines the currents, voltages, transist
     &or'
      PRINT*,'commutation times and the resonant component values for'
      PRINT*,'the Single Phase Cascaded Schwarz Converters.  The user'
      PRINT*,'is required to input the following data at execution tim
     &e'
      PRINT*
      PRINT*,'     VS1 = The input voltage to stage one.'
      PRINT*,'     VO2 = The output voltage of stage two.'
      PRINT*,'     IA2 = The average output current of stage two.'
      PRINT*,'     N1  = Stage one transformer turns ratio (N1/N2).'
      PRINT*,'     N2  = Stage two transformer turns ratio (N1/N2).'
      PRINT*,'     NU1 = Stage one efficiency.'
      PRINT*,'     NU2 = Stage two efficiency.'
```

```
      PRINT*,'    K12 = The ratio of the characteristic impedance of'
      PRINT*,'          stage one to the characteristic impedance of'
      PRINT*,'          stage two.'
      PRINT*,'    FO1 = The resonant frequency of stage one.'
      PRINT*,'    FS1MAX = The maximum operating frequency of stage one.
     &'
      PRINT*,'    FO2 = The resonant frequency of stage two.'
      PRINT*,'    FS2 = The fixed operating frequency of stage two.'
      PRINT*
C-----------------------------------------------------------------------
C     READ KNOWN VARIABLES
C-----------------------------------------------------------------------
10    PRINT*
      PRINT*
      WRITE(6,20)
20    FORMAT(' (*) VS1 (in volts D.C.) = >>>>>',$)
      READ*,VS1
      WRITE(6,30)
30    FORMAT(' (*) VO2 (in volts D.C.) = >>>>>',$)
      READ*,VO2
      WRITE(6,40)
40    FORMAT(' (*) IA2 (in amps D.C.) = >>>>>>',$)
      READ*,IA2
      WRITE(6,50)
50    FORMAT(' (*) N1 (ratio in decimal) = >>>',$)
      READ*,N1
      WRITE(6,60)
60    FORMAT(' (*) N2 (ratio in decimal) = >>>',$)
      READ*,N2
      WRITE(6,70)
70    FORMAT(' (*) NU1 (in decimal) = >>>>>>>>',$)
      READ*,NU1
      WRITE(6,80)
80    FORMAT(' (*) NU2 (in decimal) = >>>>>>>>',$)
      READ*,NU2
      WRITE(6,90)
90    FORMAT(' (*) K12 (in decimal) = >>>>>>>>',$)
      READ*,K12
      WRITE(6,100)
100   FORMAT(' (*) FO1 (in Hertz) = >>>>>>>>>>',$)
      READ*,FO1
      WRITE(6,110)
110   FORMAT(' (*) FS1MAX (in Hertz) = >>>>>>>',$)
      READ*,FS1MAX
      WRITE(6,120)
120   FORMAT(' (*) FO2 (in Hertz) = >>>>>>>>>>',$)
      READ*,FO2
      WRITE(6,130)
130   FORMAT(' (*) FS2 (in Hertz) = >>>>>>>>>>',$)
      READ*,FS2
C-----------------------------------------------------------------------
C     CALCULATE THE COMPENSATED INPUT AND OUTPUT VOLTAGE FOR THE GIVEN
C     EFFICIENCY
C-----------------------------------------------------------------------
```

```
      VS1EFF=VS1*NU1
C
C     CALCULATE THE COMPENSATED OUTPUT VOLTAGE FOR THE GIVEN EFFICIENCY
C
      VO2EFF=VO2/NU2
C-----------------------------------------------------------------------
C     REFLECT INPUT VOLTAGE OF STAGE ONE TO ITS TRANSFORMER SECONDARY
C-----------------------------------------------------------------------
      VS1R=VS1EFF/N1
C-----------------------------------------------------------------------
C     REFLECT OUTPUT VOLTAGE AND CURRENT OF STAGE TWO TO ITS
C     TRANSFORMER PRIMARY
C-----------------------------------------------------------------------
      VO2R=VO2EFF*N2
      IA2R=IA2/N2
C-----------------------------------------------------------------------
C     REFLECT K12 TO THE SECONDARY OF THE STAGE ONE TRANSFORMER
C-----------------------------------------------------------------------
      K12R=K12/(N1*N1)
C-----------------------------------------------------------------------
C     CALCULATE KNOWN CONSTANTS
C-----------------------------------------------------------------------
      PI=3.1415927
      GAMMA1=PI*FO1/FS1MAX
      GAMMA2=PI*FO2/FS2
      Q12R=VO2R/VS1R
C-----------------------------------------------------------------------
C     DETERMINE INITIAL VALUES OF ALPHA1, ALPHA2, AND Q1R
C-----------------------------------------------------------------------
      IF(Q12R.GE.0.9) THEN
         ALPHA1=0.34906585
         ALPHA2=ALPHA1
         Q1R=SQRT(Q12R)
      ENDIF
C
      IF(Q12R.GE.0.8.AND.Q12R.LT.0.9) THEN
         ALPHA1=0.436332313
         ALPHA2=ALPHA1
         Q1R=SQRT(Q12R)
      ENDIF
C
      IF(Q12R.GE.0.7.AND.Q12R.LT.0.8) THEN
         ALPHA1=0.37815467
         ALPHA21=ALPHA12
         Q1R=SQRT(Q12R)
      ENDIF
C
      IF(Q12R.GE.0.6.AND.Q12R.LT.0.7) THEN
         ALPHA1=0.36041049
         ALPHA2=ALPHA1
         Q1R=SQRT(Q12R)
      ENDIF
C
      IF(Q12R.GE.0.5.AND.Q12R.LT.0.6) THEN
```

```
          ALPHA1=1.221730476
          ALPHA2=ALPHA1
          Q1R=0.65
       ENDIF
C
       IF(Q12R.GE.0.4.AND.Q12R.LT.0.5) THEN
          ALPHA1=0.959931088
          ALPHA2=ALPHA1
          Q1R=0.55
       ENDIF
C
       IF(Q12R.LT.0.4) THEN
          ALPHA1=0.959931088
          ALPHA2=ALPHA1
          Q1R=0.5
       ENDIF
C-----------------------------------------------------------------------
C      SET PARAMETERS TO BE USED BY IMSL SUBROUTINE "ZSPOW"
C-----------------------------------------------------------------------
       N=3
       NSIG=4
       ITMAX=400
       X(1)=Q1R
       X(2)=ALPHA1
       X(3)=ALPHA2
       PAR(1)=GAMMA1
       PAR(2)=GAMMA2
       PAR(3)=K12R
       PAR(4)=PI
       PAR(5)=Q12R
C-----------------------------------------------------------------------
C      CALL IMSL SUBROUTINE "ZSPOW"
C-----------------------------------------------------------------------
       CALL ZSPOW(FCN,NSIG,N,ITMAX,PAR,X,FNORM,WK,IER)
C-----------------------------------------------------------------------
C      CHECK FOR ERRORS FROM IMSL SUBROUTINE "ZSPOW"
C-----------------------------------------------------------------------
       IF(IER.GT.0)THEN
          PRINT*,'ERROR EXISTS IN IMSL SUBROUTINE, IER = ',IER
          GOTO 400
       ENDIF
C-----------------------------------------------------------------------
C      CALCULATE Q2R
C-----------------------------------------------------------------------
       Q1R=X(1)
       ALPHA1=X(2)
       ALPHA2=X(3)
       Q2R=Q12R/Q1R
C-----------------------------------------------------------------------
C      DETERMINE IF THE "Q" VALUES HAVE EXCEED THEIR LIMIT
C-----------------------------------------------------------------------
       IF(Q1R.GT.0.998.OR.Q2R.GT.0.998.OR.Q12R.GT.0.998)THEN
          PRINT*
          PRINT*,'Q1R = ',Q1R,' Q2R = ',Q2R,' Q12R = ',Q12R
```

```
          PRINT*
          PRINT*,'Changes must be made to the input values such that'
          PRINT*,'these "Q" values do not exceed the limit of 0.998.'
          PRINT*,'For "Q" values greater than this limit the region of'
          PRINT*,'validity for the nonlinear equations may be exceeded.'
          PRINT*
          GOTO 400
       ENDIF
C-----------------------------------------------------------------------
C      DETERMINE IF ALPHA1 AND ALPHA2 ARE LESS THAN THEIR REQUIRED
C      MINIMUM VLAUES
C-----------------------------------------------------------------------
          AL1MIN=ACOS(Q1R)
          AL2MIN=ACOS(Q2R)
C
       IF(ALPHA1.LT.AL1MIN)THEN
          PRINT*,'THE VALUE OF ALPHA1 IS LESS THAN THE MINIMUM'
          PRINT*,'ACCEPTABLE LIMIT OF ',AL1MIN*180.0/PI
          GOTO 400
       ENDIF
C
       IF(ALPHA2.LT.AL2MIN)THEN
          PRINT*,'THE VALUE OF ALPHA2 IS LESS THAN THE MINIMUM'
          PRINT*,'ACCEPTABLE LIMIT OF ',AL2MIN*180.0/PI
          GOTO 400
       ENDIF
C-----------------------------------------------------------------------
C      CALCULATE THE NORMALIZED AVERAGE OUTPUT CURRENT OF STAGE ONE
C      AND TWO
C-----------------------------------------------------------------------
       IA1NR=(2*(1+Q1R)*(1-COS(ALPHA1)))/(GAMMA1*(Q1R-COS(ALPHA1)))
       IA2N=(2*(1+Q2R)*(1-COS(ALPHA2)))/(GAMMA2*Q2R*(Q2R-COS(ALPHA2)))
C-----------------------------------------------------------------------
C      CALCULATE THE NORMALIZED PEAK CUURENT OF STAGE ONE AND TWO
C -----------------------------------------------------------------------
       IPK1NR=(1+Q1R*Q1R-2*Q1R*COS(ALPHA1))/(Q1R-COS(ALPHA1))
       IPK2N=(1+Q2R*Q2R-2*Q2R*COS(ALPHA2))/(Q2R*(Q2R-COS(ALPHA2)))
C-----------------------------------------------------------------------
C      CALCULATE THE NORMALIZED AVERAGE TRANSISTOR CURRENT OF STAGE ONE
C      AND TWO
C-----------------------------------------------------------------------
       IQA1NR=(1+Q1R)*IA1NR/4
       IQA2N=(1+Q2R)*IA2N/4
C-----------------------------------------------------------------------
C      CALCULATE THE NORMAIZED AVERAGE DIODE CURRENT OF STAGE ONE
C      AND TWO
C-----------------------------------------------------------------------
       IDA1NR=(1-Q1R)*IA1NR/4
       IDA2N=(1-Q2R)*IA2N/4
C-----------------------------------------------------------------------
C      CALCULATE BETA1 AND BETA2
C-----------------------------------------------------------------------
       BETA1=PI+ATAN((Q1R*Q1R-1)*SIN(ALPHA1)/(2*Q1R-(1+Q1R*Q1R)*
      &COS(ALPHA1)))
```

```
      BETA2=PI+ATAN((Q2R*Q2R-1)*SIN(ALPHA2)/(2*Q2R-(1+Q2R*Q2R)*
     &COS(ALPHA2)))
C-----------------------------------------------------------------------
C     CALCULATE CONSTANTS FOR DETERMINING IRM1NR AND IRMS2N
C-----------------------------------------------------------------------
      IO1NR=(1-Q1R*Q1R)*SIN(ALPHA1)/(Q1R-COS(ALPHA1))
      IO2N=(1-Q2R*Q2R)*SIN(ALPHA2)/(Q2R*(Q2R-COS(ALPHA2)))
      VCO1NR=Q1R*(1+Q1R)*(1-COS(ALPHA1))/(Q1R-COS(ALPHA1))
      VCO2N=(1+Q2R)*(1-COS(ALPHA2))/(Q2R-COS(ALPHA2))
      VC11NR=-VCO1NR/Q1R
      VC12N=-VCO2N/Q2R
C-----------------------------------------------------------------------
C     CALCULATE THE NORMALIZED RMS CURRENT OF STAGE ONE AND TWO
C-----------------------------------------------------------------------
      IRM1NR=SQRT((IO1NR*IO1NR*(0.5*BETA1+0.25*SIN(2*BETA1))+(VCO1NR
     &+1-Q1R)*(VCO1NR+1-Q1R)*(0.5*BETA1-0.25*SIN(2*BETA1))+IO1NR*(
     &VCO1NR+1-Q1R)*SIN(BETA1)*SIN(BETA1)+(VC11NR+1+Q1R)*(VC11NR+1+
     &Q1R)*(0.5*ALPHA1-0.25*SIN(2*ALPHA1)))/GAMMA1)
C
      IRMS2N=SQRT((IO2N*IO2N*(0.5*BETA2+0.25*SIN(2*BETA2))+(VCO2N+
     &(1/Q2R)-1)*(VCO2N+(1/Q2R)-1)*(0.5*BETA2-0.25*SIN(2*BETA2))+IO2N
     &*(VCO2N+(1/Q2R)-1)*SIN(BETA2)*SIN(BETA2)+(VC12N+(1/Q2R)+1)*(
     &VC12N+(1/Q2R)+1)*(0.5*ALPHA2-0.25*SIN(2*ALPHA2)))/GAMMA2)
C-----------------------------------------------------------------------
C     CALCULATE THE NORMALIZED PEAK CAPACITOR VOLTAGE OF STAGE ONE
C     AND TWO
C-----------------------------------------------------------------------
      VCP1NR=-VC11NR
      VCPK2N=-VC12N
C-----------------------------------------------------------------------
C     CALCULATE THE CHARATERISTIC IMPEDANCE OF STAGE ONE AND TWO
C-----------------------------------------------------------------------
      ZO2=VO2R*IA2N/IA2R
      ZO1R=K12R*ZO2
C-----------------------------------------------------------------------
C     CALCULATE THE BASE CURRENTS FOR STAGE ONE AND TWO
C -----------------------------------------------------------------------
      IB1R=VS1R/ZO1R
      IB2R=VO2R/ZO2
C-----------------------------------------------------------------------
C     DETERMINE THE BASE BASE VOLTAGES
C-----------------------------------------------------------------------
      VB1R=VS1R
      VB2R=VO2R
C-----------------------------------------------------------------------
C     DETERMINE THE ACTUAL REFLECTED STAGE ONE CURRENTS AND VOLTAGES
C-----------------------------------------------------------------------
      IA1R=IB1R*IA1NR
      IDA1R=IB1R*IDA1NR
      IPK1R=IB1R*IPK1NR
      IQA1R=IB1R*IQA1NR
      IRMS1R=IB1R*IRM1NR
      VCPK1R=VB1R*VCP1NR
C-----------------------------------------------------------------------
```

```
C     DETERMINE THE ACTUAL STAGE TWO CURRENTS AND VOLTAGES
C-------------------------------------------------------------------
      IA2R=IB2R*IA2N
      IDA2=IB2R*IDA2N
      IPK2=IB2R*IPK2N
      IQA2=IB2R*IQA2N
      IRMS2=IB2R*IRMS2N
      VCPK2=VB2R*VCPK2N
C-------------------------------------------------------------------
C     REFLECT THE STAGE ONE QUANTITIES BACK TO THE PRIMARY SIDE OF THE
C     STAGE ONE TRANSFORMER
C-------------------------------------------------------------------
      IA1=IA1R/N1
      IDA1=IDA1R/N1
      IPK1=IPK1R/N1
      IQA1=IQA1R/N1
      IRMS1=IRMS1R/N1
      VCPK1=VCPK1R*N1
      Z01=Z01R*N1*N1
C-------------------------------------------------------------------
C     CALCULATE THE RADIAN RESONANT FREQUENCY OF STAGE ONE AND TWO
C-------------------------------------------------------------------
      WO1=2*PI*F01
      WO2=2*PI*F02
C-------------------------------------------------------------------
C     CALCULATE THE VALUE OF THE RESONANT CAPACITOR OF STAGE ONE
C     AND TWO
C-------------------------------------------------------------------
      C1=1/(Z01*W01)
      C2=1/(Z02*W02)
C-------------------------------------------------------------------
C     CALCULATE THE VALUE OF THE RESONANT INDUCTOR OF STAGE ONE
C     AND TWO
C-------------------------------------------------------------------
      L1=Z01*Z01*C1
      L2=Z02*Z02*C2
C-------------------------------------------------------------------
C     DETERMINE THE TRANSISTOR COMMUTATION TIMES
C-------------------------------------------------------------------
      T1Q=ALPHA1/WO1
      T2Q=ALPHA2/WO2
C-------------------------------------------------------------------
C     PRINT RESULTS
C-------------------------------------------------------------------
      PRINT*
      PRINT*
      PRINT*
      WRITE(6,200)
200   FORMAT('0','IA1 (amps)',2X,'IDA1 (amps)',2X,'IPK1 (amps)',2X,
     &'IQA1 (amps)',2X,'IRMS1 (amps)',3X,'VCPK1 (volts)')
      WRITE(6,210),IA1,IDA1,IPK1,IQA1,IRMS1,VCPK1
210   FORMAT(' ',F8.3,4X,F8.3,5X,F8.3,5X,F8.3,6X,F8.3,7X,F8.2)
      PRINT*
      WRITE(6,220)
```

```
220   FORMAT('0','IA2R (amps)',2X,'IDA2 (amps)',2X,'IPK2 (amps)',2X
     &'IQA2 (amps)',2X,'IRMS2 (amps)',3X,'VCPK2 (volts)')
      WRITE(6,210).IA2R,IDA2,IPK2,IQA2,IRMS2,VCPK2
      PRINT*
      WRITE(6,230)
230   FORMAT('0','C1 (farads)',3X,'L1 (henrys)',4X,'Z01 (ohms)',3X,
     &'C2 (farads)'3X'L2 (henrys)',3X,'Z02 (ohms)')
      WRITE(6,240),C1,L1,Z01,C2,L2,Z02
240   FORMAT(' ',E11.4,3X,E11.4,3X,E11.4,3X,E11.4,3X,E11.4,2X,E11.4)
      PRINT*
      WRITE(6,250)
250   FORMAT('0','ALPHA1 (deg)',2x,'ALPHA2 (deg)',3X,'T1Q (sec)
     &',4X,'T2Q (sec)',3X,'GAMMA1 (deg)',2X,'GAMMA2 (deg)')
      WRITE(6,260),ALPHA1*180/PI,ALPHA2*180/PI,T1Q,T2Q,GAMMA1*180/PI,
     &GAMMA2*180/PI
260   FORMAT(' ',1X,F6.2,9X,F6.2,6X,E11.4,2X,E11.4,5X,F6.2,8X,F6.2)
      PRINT*
      WRITE(6,270)
270   FORMAT('0',2X,'Q1R',8X,'Q2R',7X,'Q12R',8X,'VO1R')
      WRITE(6,280),Q1R,Q2R,Q12R,VS1R*Q1R
280   FORMAT(' ',F6.4,5X,F6.4,5X,F6.4,5X,F8.4)
      PRINT*
C-----------------------------------------------------------------------
C     DETERMINE IF PROGRAM SHOULD BE EXECUTED AGAIN
C-----------------------------------------------------------------------
400   WRITE(6,410)
410   FORMAT('0','DO YOU WISH TO INPUT MORE DATA? Y=1/N=2',$)
      READ*,A
      IF(A.EQ.1)THEN
         GOTO 10
      ENDIF
1000  STOP
      END
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      SUBROUTINE FCN(X,F,N,PAR)
C-----------------------------------------------------------------------
C     DECLARE VARIABLES
C-----------------------------------------------------------------------
      INTEGER N
C
      REAL X(N),F(N),PAR(5)
C-----------------------------------------------------------------------
C     EXPRESS NONLINEAR FUNCTIONS TO BE SOLVED
C-----------------------------------------------------------------------
      F(1)=(1.0+X(1))*(1.0-COS(X(2)))*(PAR(5)-X(1)*COS(X(3)))*PAR
     &(2)-PAR(5)*PAR(3)*PAR(1)*(X(1)-COS(X(2)))*(X(1)+PAR(5))*(1.0-
     &COS(X(3)))
C
```

```
      F(2)=PAR(1)-X(2)-PAR(4)-ATAN((X(1)*X(1)-1.0)*SIN(X(2))/(2.0*
     &X(1)-(1.0+X(1)*X(1))*COS(X(2))))
C
      F(3)=PAR(2)-X(3)-PAR(4)-ATAN((PAR(5)*PAR(5)-X(1)*X(1))*SIN
     &(X(3))/(2.0*X(1)*PAR(5)-(X(1)*X(1)+PAR(5)*PAR(5))*COS(X(3))))
C-----------------------------------------------------------------------
C     RETURN TO CALLING PROGRAM
C-----------------------------------------------------------------------
      RETURN
      END
```

```
Rmt$ run spcs1

This program determines the currents, voltages, transistor
commutation times and the resonant component values for
the Single Phase Cascaded Schwarz Converters.  The user
is required to input the following data at execution time

     VS1 = The input voltage to stage one.
     VO2 = The output voltage of stage two.
     IA2 = The average output current of stage two.
     N1  = Stage one transformer turns ratio (N1/N2).
     N2  = Stage two transformer turns ratio (N1/N2).
     NU1 = Stage one efficiency.
     NU2 = Stage two efficiency.
     K12 = The ratio of the characteristic impedance of
           stage one to the characteristic impedance of
           stage two.
     FO1 = The resonant frequency of stage one.
     FS1MAX = The maximum operating frequency of stage one.
     FO2 = The resonant frequency of stage two.
     FS2 = The fixed operating frequency of stage two.


(*) VS1 (in volts D.C.) = >>>>>240.0
(*) VO2 (in volts D.C.) = >>>>>197.0
(*) IA2 (in amps D.C.) = >>>>>>3.9
(*) N1 (ratio in decimal) = >>>1.0
(*) N2 (ratio in decimal) = >>>1.0
(*) NU1 (in decimal) = >>>>>>>>0.954
(*) NU2 (in decimal) = >>>>>>>>0.954
(*) K12 (in decimal) = >>>>>>>>0.48
(*) FO1 (in Hertz) = >>>>>>>>>>19230.0
(*) FS1MAX (in Hertz) = >>>>>>>13521.0
(*) FO2 (in Hertz) = >>>>>>>>>>21500.0
(*) FS2 (in Hertz) = >>>>>>>>>>19846.0


IA1 (amps)  IDA1 (amps)  IPK1 (amps)  IQA1 (amps)  IRMS1 (amps)  VCPK1 (volts)
   3.691       0.043        8.059        1.802        4.782         474.57

IA2R (amps)  IDA2 (amps)  IPK2 (amps)  IQA2 (amps)  IRMS2 (amps)  VCPK2 (volts
   3.900        0.052        6.539        1.898        4.449         795.67

C1 (farads)  L1 (henrys)   ZO1 (ohms)   C2 (farads)  L2 (henrys)  ZO2 (ohms
 0.1438E-06   0.4763E-03   0.5755E+02   0.6174E-07   0.8875E-03   0.1199E+0

ALPHA1 (deg)  ALPHA2 (deg)  T1Q (sec)   T2Q (sec)   GAMMA1 (deg)  GAMMA2 (deg
  79.34          27.72      0.1146E-04  0.3581E-05     256.00        195.00

  Q1R         Q2R         Q12R         VO1R
0.9529      0.9465      0.9019      218.1705
```

Appendix D

SINGLE PHASE PARALLEL MODULE CASCADED SCHWARZ CONVERTER DESIGN PROGRAM

```
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
C     SINGLE PHASE PARALLEL MODULE CASCADED SCHWARZ CONVERTER
C     DESIGN PROGRAM
C
C     Author: Russell E. Shetler, Jr.
C
C     Description:
C
C        This program determines the currents, voltages, transistor
C        commutation times and resonant component values for the design
C        of the single phase parallel module cascaded Schwarz converter.
C        The user must supply the following data at execution time:
C
C           DC input voltage to stage one,
C           DC output voltage of stage two,
C           Average DC output current of stage two,
C           First stage efficiency,
C           Second stage efficiency,
C           First stage transformer turns ratio,
C           Second stage transformer turns ratio,
C           The ratio of the characteristic impedance of stage one to
C           the equivalent characteristic impedance of stage two,
C           The resonant frequency of stage one,
C           The maximum operating frequency of stage one,
C           The resonant frequency of stage two,
C           The fixed operating frequency of stage two.
C
C        The program will then generate the values for the currents,
C        voltages, commutation times and resonant components.
C
C     Algorithm:
C
C        This program uses a IMSL library subroutine "ZSPOW" to solve the
C        nonlinear equations which describe the single phase cascaded
C        Schwarz converter.
C
C     Input Format:
C
C        The required data is supplied at execution time.  The format for
C        the required data is specified by a write statament at execution
C        time.
C
C     Output Format:
C
C        The program output consists of a brief explanatory header, a
C        statement of the parameters being calculated and the values of
C        the given parameters.
C
C     Variable Dictionary:
C
C        A = Variable to determine if more data is to be entered.
C        ALPHA1 = Delay angle of stage one (an unknown).
```

```
C          ALPHA2 = Delay angle of stage two (an unknown).
C          AL1MIN = The minimum acceptable value of ALPHA1.
C          AL2MIN = The minimum acceptable value of ALPHA2.
C          C1 = The resonant capacitor of stage one.
C          C2EQ = The equivalent resonant capacitor of stage two.
C          C2M = The module resonant capacitor of stage two.
C          FCN = A subroutine which contains the nonlinear equations to be
C                solved.
C          F01 = The resonant frequency of stage one (in Hertz).
C          F02 = The resonant frequency of stage two (in Hertz).
C          FS1MAX = The maximum operating frequency of stage one (in
C                   Hertz).
C          FS2 = The fixed operating frequency of stage two (in Hertz).
C          GAMMA1 = The total conduction angle of stage one.
C          GAMMA2 = The total conduction angle of stage two.
C          IA1 = The average output current of stage one.
C          IA1NR = The normalized average output current of stage one
C                  reflected to its transformer secondary.
C          IA1R = The average output current of stage one reflected to
C                 its transformer secondary.
C          IA2 = The average output current of stage two.
C          IA2R = The average output current of stage two reflected to
C                 its transformer primary.
C          IA2N = The normalized average output current of stage two.
C          IB1R = The base current of stage one reflected to its
C                 transformer secondary.
C          IB2R = The base current of stage two reflected to its
C                 transformer primary.
C          IDA1 = The average diode current of stage one.
C          IDA1NR = The normalized average diode current of stage one
C                   reflected to its transformer secondary.
C          IDA1R = The average diode current of stage one reflected to
C                  its transformer secondary.
C          IDA2 = The average diode current of stage two.
C          IDA2N = The normalized average diode current of stage two.
C          IER = Error parameter.
C          IPK1 = The peak current of stage one.
C          IPK1NR = The normalized peak current of stage one reflected to
C                   its transformer secondary.
C          IPK1R = The peak current of stage one reflected to its
C                  transformer secondary.
C          IPK2 = The peak current of stage two.
C          IPK2N = The normalized peak current of stage two.
C          IQA1 = The average transistor current of stage one.
C          IQA1NR = The normalized average transistor current of stage one
C                   reflected to its transformer secondary.
C          IQA1R = The average transistor current of stage one reflected
C                  to its transformer secondary.
C          IQA2 = The average transistor current of stage two.
C          IQA2N = The normalized average transistor current of stage two.
C          IRMS1 = The RMS current of stage one.
C          IRM1NR = The normalized RMS current of stage one reflected to
C                   its transformer secondary.
C          IRMS1R = The RMS current of stage one reflected to its
```

```
C               transformer secondary.
C          IRMS2 = The RMS current of stage two.
C          IRMS2N = The normalized RMS current of stage two.
C          ITMAX = The maximum number of iterations.
C          IO1NR = Normalized average current of stage one at time t=0
C                  reflected to its transformer secondary.
C          IO2N = Normalized average current of stage two at time t=0.
C          K12 = The ratio of the characteristic impedance of stage one to
C                the equivalent characteristic impedance of stage two.
C          K12R = The value of K12 reflected to the secondary of the stage
C                 one transformer.
C          L1 = The resonant inductor of stage one.
C          L2EQ = The equivalent resonant inductor of stage two.
C          L2M = The module resonant inductor of stage two.
C          N = The number of equations to be solved and the number of
C              unknowns.
C          NSIG = The number of digits of accuracy desired in the computed
C                 roots.
C          NU1 = The efficiency of stage one.
C          NU2 = The efficiency of stage two.
C          N1 = The stage one transformer turns ratio (N1/N2).
C          N2 = The stage two transfomer turns ratio (N1/N2).
C          PAR(5) = A parameter set used to pass information between programs.
C          PI = A constant equal to 3.1415927.
C          Q1R = The ratio of the output voltage to the input voltage of stage
C                one (an unknown).
C          Q2R = The ratio of the output voltage to the input voltage of stage
C                two.
C          Q12R = The ratio of the ouput voltage of stage two to the input
C                 voltage of stage one.
C          T1Q = The commutation time of the stage one transistors.
C          T2Q = The commutation time of the stage two transistors.
C          VB1R = The base voltage of stage one reflected to its transformer
C                 secondary.
C          VB2R = The base voltage of stage two reflected to its transformer
C                 primary.
C          VCPK1 = The peak capacitor voltage of stage one.
C          VCP1NR = The normalized peak capacitor voltage of stage one
C                   reflected to its transformer secondary.
C          VCPK1R = The peak capacitor voltage of stage one reflected to
C                   the transformer secondary.
C          VCPK2 = The peak capacitor voltage of stage two.
C          VCPK2N = The normalized peak capacitor voltage of stage two.
C          VCO1NR = The normalized stage one capacitor voltage at time t=0
C                   reflected to its transformer secondary.
C          VCO2N = The normalized stage two capacitor voltage at time t=0.
C          VC11NR = The normalized stage one capacitor voltage at time t=1
C                   reflected to its transformer secondary.
C          VC12N = The normalized stage two capacitor voltage at time t=1.
C          VO1R = The reflected link voltage between stage one and two.
C          VO2 = The output voltage of stage two.
C          VO2EFF = The output voltage of stage two taking into account
C                   the efficeincy of stage two.
C          VO2R = The output voltage of stage two reflected to the
```

```
C              primary of its transformer.
C         VS1 = The input voltage to stage one.
C         VS1EFF = The input voltage to stage one taking into account
C                the efficeincy of stage one.
C         VS1R = The input voltage to stage one reflected to its transformer
C              secondary.
C         WK(36) = A block of memory used by ZSPOW for calculations.
C         WO1 = The radian resonant frequency of stage one.
C         WO2 = The radian resonant frequency of stage two.
C         X(3) = A vector of the unknowns: On input it contains the initial
C              guess of the roots and on output it contains the best
C              approximation to the root.
C         ZO1 = The characteristic impedance of stage one.
C         ZO1R = The characteristic impedance of stage one reflected to
C              its transformer secondary.
C         ZO2EQ = The equivalent characteristic impedance of stage two.
C         ZO2M = The module characteristic impedance of stage two.
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C---------------------------------------------------------------------
C     DECLARE VARIABLES TO BE USED
C---------------------------------------------------------------------
      INTEGER N,NSIG,ITMAX,IER,A
C
      REAL ALPHA1,ALPHA2,AL1MIN,AL2MIN,BETA1,BETA2,C1,C2EQ,C2M,FO1,FO2
      REAL FS1MAX,FS2,GAMMA1,GAMMA2,IA1,IA1NR,IA1R,IA2,IA2N,IA2R,IB1R
      REAL IB2R,IDA1,IDA1NR,IDA1R,IDA2,IDA2N,IPK1,IPK1NR,IPK1R,IPK2
      REAL IPK2N,IQA1,IQA1NR,IQA1R,IQA2,IQA2N,IRMS1,IRMINR,IRMS1R
      REAL IRMS2,IRMS2N,IO1NR,IO2N,K12,K12R,L1,L2EQ,L2M,NU1,NU2,N1,N2
      REAL PAR(5),PI,Q1R,Q2R,Q12R,T1Q,T2Q,VCPK1,VCPINR,VCPK2,VCPK2N
      REAL VCO1NR,VCO2N,VC11NR,VC12N,WK(36),WO1,WO2,X(3),VB1R,VB2R,VO2
      REAL VO2EFF,VO2R,VS1,VS1EFF,VS1R,ZO1,ZO1R,ZO2EQ,ZO2M
C---------------------------------------------------------------------
C     DECLARE EXTERNAL SUBROUTINES
C---------------------------------------------------------------------
      EXTERNAL FCN
C---------------------------------------------------------------------
C     PRINT OUTPUT HEADER
C---------------------------------------------------------------------
      PRINT*
      PRINT*
      PRINT*
      PRINT*,'This program determines the currents, voltages, transist
     &or'
      PRINT*,'commutation times and the resonant component values for'
      PRINT*,'the Single Phase Parallel Module Cascaded Schwarz'
      PRINT*,'Converter.  The user is required to input the following'
      PRINT*,'data at execution time'
      PRINT*
      PRINT*,'     VS1 = The input voltage to stage one.'
      PRINT*,'     VO2 = The output voltage of stage two.'
      PRINT*,'     IA2 = The average output current of stage two.'
```

```
      PRINT*,'    N1  = Stage one transformer turns ratio (N1/N2).'
      PRINT*,'    N2  = Stage two transformer turns ratio (N1/N2).'
      PRINT*,'    NU1 = Stage one efficiency.'
      PRINT*,'    NU2 = Stage two efficiency.'
      PRINT*,'    K12 = The ratio of the characteristic impedance of'
      PRINT*,'          stage one to the equivalent characteristc'
      PRINT*,'          impedance of stage two.'
      PRINT*,'    FO1 = The resonant frequency of stage one.'
      PRINT*,'    FS1MAX = The maximum operating frequency of stage one.
     &'
      PRINT*,'    FO2 = The resonant frequency of stage two.'
      PRINT*,'    FS2 = The fixed operating frequency of stage two.'
      PRINT*
C-----------------------------------------------------------------------
C     READ KNOWN VARIABLES
C-----------------------------------------------------------------------
10    PRINT*
      PRINT*
      WRITE(6,20)
20    FORMAT(' (*) VS1 (in volts D.C.) = >>>>>',$)
      READ*,VS1
      WRITE(6,30)
30    FORMAT(' (*) VO2 (in volts D.C.) = >>>>>',$)
      READ*,VO2
      WRITE(6,40)
40    FORMAT(' (*) IA2 (in amps D.C.) = >>>>>>',$)
      READ*,IA2
      WRITE(6,50)
50    FORMAT(' (*) N1 (ratio in decimal) = >>',$)
      READ*,N1
      WRITE(6,60)
60    FORMAT(' (*) N2 (ratio in decimal) = >>',$)
      READ*,N2
      WRITE(6,70)
70    FORMAT(' (*) NU1 (in decimal) = >>>>>>>',$)
      READ*,NU1
      WRITE(6,80)
80    FORMAT(' (*) NU2 (in decimal) = >>>>>>>',$)
      READ*,NU2
      WRITE(6,90)
90    FORMAT(' (*) K12 (in decimal) = >>>>>>>>',$)
      READ*,K12
      WRITE(6,100)
100   FORMAT(' (*) FO1 (in Hertz) = >>>>>>>>>>',$)
      READ*,FO1
      WRITE(6,110)
110   FORMAT(' (*) FS1MAX (in Hertz) = >>>>>>>',$)
      READ*,FS1MAX
      WRITE(6,120)
120   FORMAT(' (*) FO2 (in Hertz) = >>>>>>>>>>',$)
      READ*,FO2
      WRITE(6,130)
130   FORMAT(' (*) FS2 (in Hertz) = >>>>>>>>>>',$)
      READ*,FS2
```

```
      PRINT*
      PRINT*
C-------------------------------------------------------------------
C     CALCULATE THE COMPENSATED INPUT AND OUTPUT VOLTAGE FOR THE GIVEN
C     EFFICIENCY
C-------------------------------------------------------------------
      VS1EFF=VS1*NU1
      VO2EFF=VO2/NU2
C-------------------------------------------------------------------
C     REFLECT INPUT VOLTAGE OF STAGE ONE TO ITS TRANSFORMER SECONDARY
C-------------------------------------------------------------------
      VS1R=VS1EFF/N1
C-------------------------------------------------------------------
C     REFLECT OUTPUT VOLTAGE AND CURRENT OF STAGE TWO TO ITS
C     TRANSFORMER PRIMARY
C-------------------------------------------------------------------
      VO2R=VO2EFF*N2
      IA2R=IA2/N2
C-------------------------------------------------------------------
C     REFLECT K12 TO THE SECONDARY OF THE STAGE ONE TRANSFORMER
C-------------------------------------------------------------------
      K12R=K12/(N1*N1)
C-------------------------------------------------------------------
C     CALCULATE KNOWN CONSTANTS
C-------------------------------------------------------------------
      PI=3.1415927
      GAMMA1=PI*FO1/FS1MAX
      GAMMA2=PI*FO2/FS2
      Q12R=VO2R/VS1R
C-------------------------------------------------------------------
C     DETERMINE INITIAL VALUES OF ALPHA1, ALPHA2, AND Q1R
C-------------------------------------------------------------------
      IF(Q12R.GE.0.9) THEN
         ALPHA1=0.34906585
         ALPHA2=ALPHA1
         Q1R=SQRT(Q12R)
      ENDIF
C
      IF(Q12R.GE.0.8.AND.Q12R.LT.0.9) THEN
         ALPHA1=0.436332313
         ALPHA2=ALPHA1
         Q1R=SQRT(Q12R)
      ENDIF
C
      IF(Q12R.GE.0.7.AND.Q12R.LT.0.8) THEN
         ALPHA1=0.37815467
         ALPHA21=ALPHA12
         Q1R=SQRT(Q12R)
      ENDIF
C
      IF(Q12R.GE.0.6.AND.Q12R.LT.0.7) THEN
         ALPHA1=0.36041049
         ALPHA2=ALPHA1
         Q1R=SQRT(Q12R)
```

```
      ENDIF
C
      IF(Q12R.GE.0.5.AND.Q12R.LT.0.6) THEN
         ALPHA1=1.221730476
         ALPHA2=ALPHA1
         Q1R=0.65
      ENDIF
C
      IF(Q12R.GE.0.4.AND.Q12R.LT.0.5) THEN
         ALPHA1=0.959931088
         ALPHA2=ALPHA1
         Q1R=0.55
      ENDIF
C
      IF(Q12R.LT.0.4) THEN
         ALPHA1=0.959931088
         ALPHA2=ALPHA1
         Q1R=0.5
      ENDIF
C-----------------------------------------------------------------
C     SET PARAMETERS TO BE USED BY IMSL SUBROUTINE "ZSPOW"
C-----------------------------------------------------------------
      N=3
      NSIG=4
      ITMAX=400
      X(1)=Q1R
      X(2)=ALPHA1
      X(3)=ALPHA2
      PAR(1)=GAMMA1
      PAR(2)=GAMMA2
      PAR(3)=K12R
      PAR(4)=PI
      PAR(5)=Q12R
C-----------------------------------------------------------------
C     CALL IMSL SUBROUTINE "ZSPOW"
C-----------------------------------------------------------------
      CALL ZSPOW(FCN,NSIG,N,ITMAX,PAR,X,FNORM,WK,IER)
C-----------------------------------------------------------------
C     CHECK FOR ERRORS FROM IMSL SUBROUTINE "ZSPOW"
C-----------------------------------------------------------------
      IF(IER.GT.0)THEN
         PRINT*,'ERROR EXISTS IN IMSL SUBROUTINE, IER = ',IER
         GOTO 400
      ENDIF
C-----------------------------------------------------------------
C     CALCULATE Q2R
C-----------------------------------------------------------------
      Q1R=X(1)
      ALPHA1=X(2)
      ALPHA2=X(3)
      Q2R=Q12R/Q1R
C-----------------------------------------------------------------
C     DETERMINE IF THE "Q" VALUES HAVE EXCEEDED THEIR LIMIT
C-----------------------------------------------------------------
```

```
      IF(Q1R.GT.0.998.OR.Q2R.GT.0.998.OR.Q12R.GT.0.998)THEN
         PRINT*
         PRINT*,'Q1R = ',Q1R,' Q2R = ',Q2R,' Q12R = ',Q12R
         PRINT*
         PRINT*,'Changes must be made to the input values such that'
         PRINT*,'these "Q" values do not exceed the limit of 0.998.'
         PRINT*,'For "Q" values greater than this limit the region of'
         PRINT*,'validity for the nonlinear equations may be exceeded.'
         PRINT*
         GOTO 400
      ENDIF
C----------------------------------------------------------------------
C     DETERMINE IF ALPHA1 AND ALPHA2 ARE LESS THAN THEIR REQUIRED
C     MINIMUM VLAUES
C----------------------------------------------------------------------
         AL1MIN=ACOS(Q1R)
         AL2MIN=ACOS(Q2R)
C
      IF(ALPHA1.LT.AL1MIN)THEN
         PRINT*,'THE VALUE OF ALPHA1 IS LESS THAN THE MINIMUM'
         PRINT*,'ACCEPTABLE LIMIT OF ',AL1MIN*180.0/PI
         GOTO 400
      ENDIF
C
      IF(ALPHA2.LT.AL2MIN)THEN
         PRINT*,'THE VALUE OF ALPHA2 IS LESS THAN THE MINIMUM'
         PRINT*,'ACCEPTABLE LIMIT OF ',AL2MIN*180.0/PI
         GOTO 400
      ENDIF
C----------------------------------------------------------------------
C     CALCULATE THE NORMALIZED AVERAGE OUTPUT CURRENT OF STAGE ONE
C     AND TWO
C----------------------------------------------------------------------
      IA1NR=(2*(1+Q1R)*(1-COS(ALPHA1)))/(GAMMA1*(Q1R-COS(ALPHA1)))
      IA2N=(2*(1+Q2R)*(1-COS(ALPHA2)))/(GAMMA2*Q2R*(Q2R-COS(ALPHA2)))
C----------------------------------------------------------------------
C     CALCULATE THE NORMALIZED PEAK CUURENT OF STAGE ONE AND TWO
C ---------------------------------------------------------------------
      IPK1NR=(1+Q1R*Q1R-2*Q1R*COS(ALPHA1))/(Q1R-COS(ALPHA1))
      IPK2N=(1+Q2R*Q2R-2*Q2R*COS(ALPHA2))/(Q2R*(Q2R-COS(ALPHA2)))
C----------------------------------------------------------------------
C     CALCULATE THE NORMALIZED AVERAGE TRANSISTOR CURRENT OF STAGE ONE
C     AND TWO
C----------------------------------------------------------------------
      IQA1NR=(1+Q1R)*IA1NR/4
      IQA2N=(1+Q2R)*IA2N/4
C----------------------------------------------------------------------
C     CALCULATE THE NORMAIZED AVERAGE DIODE CURRENT OF STAGE ONE
C     AND TWO
C----------------------------------------------------------------------
      IDA1NR=(1-Q1R)*IA1NR/4
      IDA2N=(1-Q2R)*IA2N/4
C----------------------------------------------------------------------
C     CALCULATE BETA1 AND BETA2
```

```
C-----------------------------------------------------------------
      BETA1=PI+ATAN((Q1R*Q1R-1)*SIN(ALPHA1)/(2*Q1R-(1+Q1R*Q1R)*
     &COS(ALPHA1)))
      BETA2=PI+ATAN((Q2R*Q2R-1)*SIN(ALPHA2)/(2*Q2R-(1+Q2R*Q2R)*
     &COS(ALPHA2)))
C-----------------------------------------------------------------
C     CALCULATE CONSTANTS FOR DETERMINING IRM1NR AND IRMS2N
C-----------------------------------------------------------------
      IO1NR=(1-Q1R*Q1R)*SIN(ALPHA1)/(Q1R-COS(ALPHA1))
      IO2N=(1-Q2R*Q2R)*SIN(ALPHA2)/(Q2R*(Q2R-COS(ALPHA2)))
      VCO1NR=Q1R*(1+Q1R)*(1-COS(ALPHA1))/(Q1R-COS(ALPHA1))
      VCO2N=(1+Q2R)*(1-COS(ALPHA2))/(Q2R-COS(ALPHA2))
      VC11NR=-VCO1NR/Q1R
      VC12N=-VCO2N/Q2R
C-----------------------------------------------------------------
C     CALCULATE THE NORMALIZED RMS CURRENT OF STAGE ONE AND TWO
C-----------------------------------------------------------------
      IRM1NR=SQRT((IO1NR*IO1NR*(0.5*BETA1+0.25*SIN(2*BETA1))+(VCO1NR
     &+1-Q1R)*(VCO1NR+1-Q1R)*(0.5*BETA1-0.25*SIN(2*BETA1))+IO1NR*(
     &VCO1NR+1-Q1R)*SIN(BETA1)*SIN(BETA1)+(VC11NR+1+Q1R)*(VC11NR+1+
     &Q1R)*(0.5*ALPHA1-0.25*SIN(2*ALPHA1)))/GAMMA1)
C
      IRMS2N=SQRT((IO2N*IO2N*(0.5*BETA2+0.25*SIN(2*BETA2))+(VCO2N+
     &(1/Q2R)-1)*(VCO2N+(1/Q2R)-1)*(0.5*BETA2-0.25*SIN(2*BETA2))+IO2N
     &*(VCO2N+(1/Q2R)-1)*SIN(BETA2)*SIN(BETA2)+(VC12N+(1/Q2R)+1)*(
     &VC12N+(1/Q2R)+1)*(0.5*ALPHA2-0.25*SIN(2*ALPHA2)))/GAMMA2)
C-----------------------------------------------------------------
C     CALCULATE THE NORMALIZED PEAK CAPACITOR VOLTAGE OF STAGE ONE
C     AND TWO
C-----------------------------------------------------------------
      VCP1NR=-VC11NR
      VCPK2N=-VC12N
C-----------------------------------------------------------------
C     CALCULATE THE CHARATERISTIC IMPEDANCE OF STAGE ONE AND TWO
C-----------------------------------------------------------------
      ZO2EQ=VO2R*IA2N/IA2R
      ZO2M=3.0*ZO2EQ
      ZO1R=K12R*ZO2EQ
C-----------------------------------------------------------------
C     CALCULATE THE BASE CURRENTS FOR STAGE ONE AND TWO
C -----------------------------------------------------------------
      IB1R=VS1R/ZO1R
      IB2R=VO2R/ZO2EQ
C-----------------------------------------------------------------
C     DETERMINE THE BASE BASE VOLTAGES
C-----------------------------------------------------------------
      VB1R=VS1R
      VB2R=VO2R
C-----------------------------------------------------------------
C     DETERMINE THE ACTUAL REFLECTED STAGE ONE CURRENTS AND VOLTAGES
C-----------------------------------------------------------------
      IA1R=IB1R*IA1NR
      IDA1R=IB1R*IDA1NR
      IPK1R=IB1R*IPK1NR
```

```
      IQA1R=IB1R*IQA1NR
      IRMS1R=IB1R*IRM1NR
      VCPK1R=VB1R*VCP1NR
C-----------------------------------------------------------------
C     DETERMINE THE ACTUAL STAGE TWO CURRENTS AND VOLTAGES
C-----------------------------------------------------------------
      IA2R=IB2R*IA2N
      IDA2=IB2R*IDA2N
      IPK2=IB2R*IPK2N
      IQA2=IB2R*IQA2N
      IRMS2=IB2R*IRMS2N
      VCPK2=VB2R*VCPK2N
C-----------------------------------------------------------------
C     REFLECT THE STAGE ONE QUANTITIES BACK TO THE PRIMARY SIDE OF THE
C     STAGE ONE TRANSFORMER
C-----------------------------------------------------------------
      IA1=IA1R/N1
      IDA1=IDA1R/N1
      IPK1=IPK1R/N1
      IQA1=IQA1R/N1
      IRMS1=IRMS1R/N1
      VCPK1=VCPK1R*N1
      ZO1=ZO1R*N1*N1
C-----------------------------------------------------------------
C     CALCULATE THE RADIAN RESONANT FREQUENCY OF STAGE ONE AND TWO
C-----------------------------------------------------------------
      WO1=2*PI*FO1
      WO2=2*PI*FO2
C-----------------------------------------------------------------
C     CALCULATE THE VALUE OF THE RESONANT CAPACITOR OF STAGE ONE
C     AND TWO
C-----------------------------------------------------------------
      C1=1/(ZO1*WO1)
      C2EQ=1/(ZO2EQ*WO2)
      C2M=3.0*C2EQ
C-----------------------------------------------------------------
C     CALCULATE THE VALUE OF THE RESONANT INDUCTOR OF STAGE ONE
C     AND TWO
C-----------------------------------------------------------------
      L1=ZO1*ZO1*C1
      L2EQ=ZO2EQ*ZO2EQ*C2EQ
      L2M=L2EQ/3.0
C-----------------------------------------------------------------
C     DETERMINE THE TRANSISTOR COMMUTATION TIMES
C-----------------------------------------------------------------
      T1Q=ALPHA1/WO1
      T2Q=ALPHA2/WO2
C-----------------------------------------------------------------
C     PRINT RESULTS
C-----------------------------------------------------------------
      PRINT*
      PRINT*
      PRINT*
      PRINT*,'           *** STAGE ONE VALUES ***'
```

```
      PRINT*
      WRITE(6,200)
200   FORMAT('0','IA1 (amps)',2X,'IDA1 (amps)',2X,'IPK1 (amps)',2X,
     &'IQA1 (amps)',2X,'IRMS1 (amps)',3X,'VCPK1 (volts)')
      WRITE(6,210),IA1,IDA1,IPK1,IQA1,IRMS1,VCPK1
210   FORMAT(' ',F8.3,4X,F8.3,5X,F8.3,5X,F8.3,6X,F8.3,7X,F8.2)
      PRINT*
      WRITE(6,220)
220   FORMAT('0','C1 (farads)',3X,'L1 (henrys)',4X,'Z01 (ohms)',3X,
     &'GAMMA1 (degrees)',3X,'ALPHA1 (degrees)')
      WRITE(6,230),C1,L1,Z01,GAMMA1*180/PI,ALPHA1*180/PI
230   FORMAT(' ',E11.4,3X,E11.4,3X,E11.4,7X,F6.2,14X,F6.2)
      PRINT*
      WRITE(6,240)
240   FORMAT('0','T1Q (secs)',6X,'Q1R',7X,'Q12R',5X,'V01R (volts)')
      WRITE(6,250),T1Q,Q1R,Q12R,VS1R*Q1R
250   FORMAT(' ',E11.4,3X,F6.4,5X,F6.4,5X,F8.2)
      PRINT*
      PRINT*
      PRINT*
      PRINT*,'            *** STAGE TWO EQUIVALENT CIRCUIT VALUES ***'
      PRINT*
      WRITE(6,260)
260   FORMAT('0','IA2 (amps)',2X,'IDA2 (amps)',2X,'IPK2 (amps)',2X,
     &'IQA2 (amps)',2X,'IRMS2 (amps)',3X,'VCPK2 (volts)')
      WRITE(6,270),IA2,IDA2,IPK2,IQA2,IRMS2,VCPK2
270   FORMAT(' ',F8.3,4X,F8.3,5X,F8.3,5X,F8.3,6X,F8.3,7X,F8.2)
      PRINT*
      WRITE(6,280)
280   FORMAT('0','C2EQ (farads)',2X,'L2EQ (henrys)',2X,'Z02EQ (ohms)',2X,
     &'GAMMA2 (degrees)',2X,'ALPHA2 (degrees)')
      WRITE(6,290),C2EQ,L2EQ,Z02EQ,GAMMA2*180/PI,ALPHA2*180/PI
290   FORMAT(' ',E11.4,4X,E11.4,4X,E11.4,8X,F6.2,11X,F6.2)
      PRINT*
      WRITE(6,300)
300   FORMAT('0','T2Q (secs)',6X,'Q2R')
      WRITE(6,310),T2Q,Q2R
310   FORMAT(' ',E11.4,3X,F6.4)
      PRINT*
      PRINT*
      PRINT*
      PRINT*,'            *** STAGE TWO INDIVIDUAL MODULE VALUES ***'
      PRINT*
      WRITE(6,320)
320   FORMAT('0','IDA2M (amps)',2X,'IPK2M (amps)',2X,
     &'IQA2M (amps)',2X,'IRMS2M (amps)',3X,'VCPK2 (volts)')
      WRITE(6,330),IDA2/3,IPK2/3,IQA2/3,IRMS2/3,VCPK2
330   FORMAT(' ',F8.3,6X,F8.3,6X,F8.3,7X,F8.3,8X,F8.2)
      PRINT*
      WRITE(6,340)
340   FORMAT('0','C2M (farads)',3X,'L2M (henrys)',3X,'Z02M (ohms)',3X,
     &'GAMMA2 (degrees)',2X,'ALPHA2 (degrees)')
      WRITE(6,350),C2M,L2M,Z02M,GAMMA2*180/PI,ALPHA2*180/PI
350   FORMAT(' ',E11.4,4X,E11.4,4X,E11.4,8X,F6.2,11X,F6.2)
```

```
      PRINT*
C-----------------------------------------------------------------------
C     DETERMINE IF PROGRAM SHOULD BE EXECUTED AGAIN
C-----------------------------------------------------------------------
400   WRITE(6,410)
410   FORMAT('0','DO YOU WISH TO INPUT MORE DATA? Y=1/N=2',$)
      READ*,A
      IF(A.EQ.1)THEN
         GOTO 10
      ENDIF
1000  STOP
      END
C
C
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
C
      SUBROUTINE FCN(X,F,N,PAR)
C-----------------------------------------------------------------------
C     DECLARE VARIABLES
C-----------------------------------------------------------------------
      INTEGER N
C
      REAL X(N),F(N),PAR(5)
C-----------------------------------------------------------------------
C     EXPRESS NONLINEAR FUNCTIONS TO BE SOLVED
C-----------------------------------------------------------------------
      F(1)=(1.0+X(1))*(1.0-COS(X(2)))*(PAR(5)-X(1)*COS(X(3)))*PAR
     &(2)-PAR(5)*PAR(3)*PAR(1)*(X(1)-COS(X(2)))*(X(1)+PAR(5))*(1.0-
     &COS(X(3)))
C
      F(2)=PAR(1)-X(2)-PAR(4)-ATAN((X(1)*X(1)-1.0)*SIN(X(2))/(2.0*
     &X(1)-(1.0+X(1)*X(1))*COS(X(2))))
C
      F(3)=PAR(2)-X(3)-PAR(4)-ATAN((PAR(5)*PAR(5)-X(1)*X(1))*SIN
     &(X(3))/(2.0*X(1)*PAR(5)-(X(1)*X(1)+PAR(5)*PAR(5))*COS(X(3))))
C-----------------------------------------------------------------------
C     RETURN TO CALLING PROGRAM
C-----------------------------------------------------------------------
      RETURN
      END
```

```
Rmt$ run sppmcs

This program determines the currents, voltages, transistor
commutation times and the resonant component values for
the Single Phase Parallel Module Cascaded Schwarz
Converter.  The user is required to input the following
data at execution time

    VS1 = The input voltage to stage one.
    VO2 = The output voltage of stage two.
    IA2 = The average output current of stage two.
    N1  = Stage one transformer turns ratio (N1/N2).
    N2  = Stage two transformer turns ratio (N1/N2).
    NU1 = Stage one efficiency.
    NU2 = Stage two efficiency.
    K12 = The ratio of the characteristic impedance of
          stage one to the equivalent characteristc
          impedance of stage two.
    FO1 = The resonant frequency of stage one.
    FS1MAX = The maximum operating frequency of stage one.
    FO2 = The resonant frequency of stage two.
    FS2 = The fixed operating frequency of stage two.


(*) VS1 (in volts D.C.) = >>>>>112.0
(*) VO2 (in volts D.C.) = >>>>>203.0
(*) IA2 (in amps D.C.) = >>>>>>12.56
(*) N1 (ratio in decimal) = >>0.4
(*) N2 (ratio in decimal) = >>1.0
(*) NU1 (in decimal) = >>>>>>>0.957
(*) NU2 (in decimal) = >>>>>>>0.922
(*) K12 (in decimal) = >>>>>>>>0.154
(*) FO1 (in Hertz) = >>>>>>>>>>20833.0
(*) FS1MAX (in Hertz) = >>>>>>>18382.0
(*) FO2 (in Hertz) = >>>>>>>>>>20408.0
(*) FS2 (in Hertz) = >>>>>>>>>>18182.0


          *** STAGE ONE VALUES ***

IA1 (amps)  IDA1 (amps)  IPK1 (amps)  IQA1 (amps)  IRMS1 (amps)  VCPK1 (volts)
  27.538       0.434       47.966       13.334       16.762        313.48

C1 (farads)  L1 (henrys)  ZO1 (ohms)  GAMMA1 (degrees)  ALPHA1 (degrees)
 0.1195E-05   0.4885E-04  0.6395E+01      204.00             35.59

T1Q (secs)      Q1R       Q12R     VO1R (volts)
 0.4745E-05   0.9369     0.8217      251.05
```

*** STAGE TWO EQUIVALENT CIRCUIT VALUES ***

IA2 (amps)	IDA2 (amps)	IPK2 (amps)	IQA2 (amps)	IRMS2 (amps)	VCPK2 (volts)
12.560	0.386	21.401	5.894	14.357	919.51

C2EQ (farads)	L2EQ (henrys)	Z02EQ (ohms)	GAMMA2 (degrees)	ALPHA2 (degrees)
0.1878E-06	0.3238E-03	0.4152E+02	202.04	41.61

T2Q (secs)	Q2R
0.5663E-05	0.8770

*** STAGE TWO INDIVIDUAL MODULE VALUES ***

IDA2M (amps)	IPK2M (amps)	IQA2M (amps)	IRMS2M (amps)	VCPK2 (volts)
0.129	7.134	1.965	4.786	919.51

C2M (farads)	L2M (henrys)	Z02M (ohms)	GAMMA2 (degrees)	ALPHA2 (degrees)
0.6261E-07	0.9715E-03	0.1246E+03	202.04	41.61

```
DO YOU WISH TO INPUT MORE DATA? Y=1/N=2
2
FORTRAN STOP
```


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